

SENSORIMOTOR SYNCHRONIZATION  
IN AUDITORY, VISUAL, AND INTERPERSONAL CONTEXTS

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# SENSORIMOTOR SYNCHRONIZATION IN AUDITORY, VISUAL, AND INTERPERSONAL CONTEXTS

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This dissertation uses finger tapping to explore sensorimotor synchronization (SMS) in auditory (Chapter 2), visual (Chapter 3), and interpersonal (Chapter 4) contexts. The experiments presented here provide evidence for shared representations for perception and action codes. Chapter 1 reviews theoretical background relevant to SMS and perception-action links, and offers an overview of the present work and future directions.

Musical ensemble performance requires synchronizing with sequences of chords containing multiple tones with multiple onsets. Chapter 2 investigates whether sensorimotor synchronization with chord sequences containing tone-onset asynchronies is affected by the magnitude of these asynchronies (25, 30, or 50 ms) and the pitch of the leading tone (high vs. low). Results indicate that tap timing was determined by a chord's subjective onset or perceptual center, and that lower pitch tones were especially influential for tap timing. Additionally, chords with nonsimultaneous onsets increased tapping variability for non-musicians, but decreased variability for musicians.

Chapter 3 examines visuomotor synchronization. Prior research indicates that synchronized tapping performance is very poor with flashing visual stimuli compared with auditory stimuli. This observed difference may reflect a general auditory advantage for processing temporal information, while visual processing may have an

advantage with spatial information. Three finger-tapping experiments compared flashing and fading visual metronomes with visual metronomes containing a spatial component, either compatible, incompatible, or orthogonal to the tapping action. Results indicate that visuomotor synchronization improves dramatically with compatible spatial information (translation over time). However, an auditory advantage in sensorimotor synchronization persists.

Chapter 4 examines interpersonal synchronization. The tendency to mimic and synchronize with others is well established. Although mimicry has been shown to lead to affiliation between co-actors, the effect of interpersonal synchrony on affiliation remains an open question. Participants matched finger movements with a visual moving metronome, while an experimenter either a) tapped to a metronome that was synchronous to the participant's metronome, b) tapped to a metronome that was asynchronous, or c) did not tap. As hypothesized the degree of synchrony predicted subsequent affiliation ratings. A control experiment found that the affiliative effects were unique to *interpersonal* synchrony.

## BIOGRAPHICAL SKETCH

Michael Hove was born in Minnesota and grew up in Menomonie, Wisconsin. After high school, he was an exchange student at Kantonsschule Zofingen in Switzerland. He attended Washington University in St. Louis, where he earned degrees in German and in Philosophy-Neuroscience-Psychology, an interdisciplinary major he helped design. In college, Mike played drums, bass, and keyboards in numerous bands, built audio gear, played on the hockey team, and worked odd jobs, including two fondue waiter/chef jobs. After graduation he moved to Munich, Germany, where he planned to live for a few months until his money ran out. Four years later, he realized that he earned a Masters degree in Educational Psychology from Ludwig-Maximilians-Universität in Munich, worked as a research associate at the Max Planck Institute for Psychological Research, translated for Siemens, organized cancer research conferences, led tours through Munich, and worked as a docent at the Dachau Memorial Site. He traveled a fair amount during this phase, including long hitchhiking adventures through Eastern Europe and Turkey and a three-month tabla and meditation sojourn in India. In grad school at Cornell, he studied rhythmic sensorimotor synchronization and perception-action links. He also pursued activities that induced absorption, including meditation, music, and hockey.

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Om nama shivaya.

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## CHAPTER 1

### INTRODUCTION, OVERVIEW, AND FUTURE DIRECTIONS

#### 1.1. Introduction

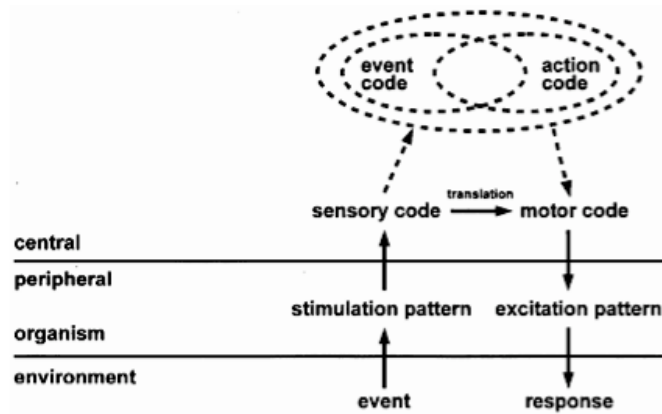
Sensorimotor synchronization (SMS) is of great theoretical and experimental interest in psychology and cognitive neuroscience. SMS can elucidate many areas of current interest including the nature of perception and action representations and how they interface, the representation of time, and aspects of social cognition. SMS is necessary for a wide variety of common tasks such as stepping on an escalator, dancing to a beat, or synchronizing movements with other musical ensemble members. The principal experimental paradigm to explore SMS uses finger tapping in synchrony with an external pacing stimulus. This technique dates back over a century (Stevens, 1886) and is still thriving (see Repp, 2005, for a recent review).

This dissertation uses finger tapping to explore sensorimotor synchronization in auditory, visual, and interpersonal contexts. It departs from the traditional and long-dominant view in cognitive psychology that perception, action, cognition, and time are processed in encapsulated modules. None of these areas can be meaningfully investigated in complete isolation. In sensorimotor synchronization, neither perception nor action leads; rather SMS is, by definition, a task of “continuous reciprocal causality” between perception and action (cf. Merleau-Ponty, 1945). The vast majority of experimental results on rhythm perception have parallel results in rhythm production, suggesting a strong link between rhythm perception and

production (Krumhansl, 2000). A powerful theoretical framework describing the perception-action interface posits that perception and action plans are coded in a common representational medium (Hommel, Müsseler, Aschersleben, & Prinz, 2001). The experiments presented here support tight perception-action linkages as proposed by common coding (Prinz, 1997) and mirror neuron theories (Rizzolatti & Craighero, 2004). Evidence for such linkages is provided in multiple domains and more specifically stems from the subjective alignment of the timing of taps and auditory chords (Chapter 2), compatibility effects between action and visual stimuli (Chapter 3), and the extension of shared perception-action codes to overlapping representations of self-other (Chapter 4).

## 1.2. Perception-Action Links

Most frameworks for the interface between perception and action systems treat perception and action codes as separate, incommensurate entities that require a translation or mapping mechanism (e.g., Massaro, 1990). Common coding theory postulates that perceptual events and action plans are coded in a shared representational space (Hommel, Müsseler, Aschersleben, & Prinz, 2001; Prinz, 1997). Rather than requiring a translation between sensory signals and action plans, they converge on integrated, task-tuned “event codes” (Figure 1.1).



*Figure 1.1.* Representations of perception and action. Solid lines represent a perception-action integration that requires a translation between sensory and motor codes, whereas the dotted lines represent shared event codes for perception and action plans (adapted from Prinz, 1997).

Tight linkages between perception and action have deep theoretical roots that date back to the ideomotor theory first developed by Lotze (1852) and James (1890). The ideomotor principle is a simple but powerful framework for understanding perception-action links and action control (Prinz, Aschersleben, & Koch, 2009). Simply imagining or thinking of a movement can lead to that movement; or in James’s (1890) words: “Every representation of a movement awakens in some degree the actual movement which is its object” (p. 1134). This sounds magical at first, but both Lotze and James argue that these linkages between the representations of movements and the actual movements arise from learned associations. Over the course of development, the “representations coding the perceivable bodily and environmental consequences of movements will become associated with representations coding the movements themselves” (Prinz, Aschersleben, & Koch, 2009, p. 38).

These associations between perceptual effects and motor commands can be used in two ways. First, the associations can predict the sensory consequences of a motor

command, as espoused by theories of *forward models* in motor control (e.g., Wolpert & Ghahramani, 2004). Forward models predictively simulate perceptual feedback of a motor command via an efference copy. This prediction can occur *during* an action to smooth movement trajectories and decrease error by anticipating feedback before the actual arrival of the much slower sensory feedback; or *prior to* action to provide information about possible actions. Second, the associations between perceptual consequences and motor commands work in the opposite direction for action selection: If you know the desired effect, you can work backward to select the motor command that will produce the desired effect. These processes are known as *inverse models* (e.g., Wolpert, Miall, & Kawato, 1998).

Ideomotor theory was originally intended to show how *thinking of an action* can lead to that action; by same logic of associations, *perceiving an action* should be even more effective at leading to that same action (Prinz, Aschersleben, & Koch, 2009). A vast body of literature shows that the perception of an event will prime the production of similar events (e.g., Greenwald, 1970). This finding has three important implications for perception/action codes as laid out by Prinz and colleagues (1997, 2009): ideomotor mapping, common coding, and distal reference. *Ideomotor mapping*, as mentioned, refers to learning associations between perceptual effects and motor commands and subsequently using those associations in action selection (inverse computation) and predicting perceptual effects (forward computation). *Common coding* refers to shared representations for perception and action codes. The shared representational domain lies ‘on top of’ separate modality coding, at the level of ‘late’ afferent representations (referring to events in the environment) and ‘early’ efferent representations (referring to intended events); hence it is sometimes called the theory of event coding (Hommel, Müsseler, Aschersleben, & Prinz, 2001). Actions are represented in terms of their perceptual effects; translations and mapping rules are

not required. Finally, *distal reference* suggests that the representational content of perceptual and action events refer to the events in the environment, rather than the proximal sensory stimulation or muscle activation patterns. These themes will return throughout this work, with common coding most prominent.

A wealth of evidence from stimulus-response compatibility research supports common coding and is consistent with the theory of dimensional overlap (Kornblum, Hasbroucq, & Osman 1990). The Simon task, for example, shows faster response times and lower error rates when stimulus and response are spatially compatible and when the dimensional overlap is greatest (Simon, 1969). Perception can prime action based on the compatibility between perceived events and to-be-produced events. In Chapter 3, experiments on visuomotor synchronization test compatibility effects between moving visual metronomes and finger movements. If perception and action (and timing) systems were isolated modules, then in a synchronization task perceptual systems would extract stimulus timing and subsequently send this information to action systems -- the stimulus orientation (compatible, incompatible, or orthogonal to finger movements) should not affect movement. However, strong compatibility effects were observed thus supporting common coding of perception and action.

While most traditional approaches treat perception and action as isolated systems, a number of approaches related to common coding stress the tight linkages between perception and action systems. The motor theory of speech perception stresses the role of motor contributions in speech perception (Liberman & Mattingly, 1985).<sup>1</sup> A non-representational approach that stresses perception-action links is

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<sup>1</sup> The motor theory was used as evidence for a modular perspective and for the claim that speech is special (e.g., we hear speech, whereas animals just hear sounds).

ecological psychology with its discussions of affordances and direct perception (Gibson, 1979).<sup>2</sup> The embodied cognition approach treats perception and action as tightly coupled systems that continuously influence each other in “continuous reciprocal causation” (Varela, Thompson, & Rosch, 1991). This perception-action coupling naturally extends to brain-body-environment coupling (Clark, 1997).

Neural support for perception-action overlap has been provided by work on mirror neuron systems. Mirror neurons, originally discovered in macaques, fire both when perceiving and producing the same action (Rizzolatti & Craighero, 2004). While direct evidence from single neuron recordings in humans is lacking, a rich amount of data indirectly supports mirror systems in humans. Neuroimaging studies show that observing another’s action activates a complex cortical network including predominantly motor areas; the ventral premotor area, the inferior parietal lobule, plus the inferior frontal gyrus form the core of the human mirror system. The mirror system has garnered great attention for its putative role in action observation and action understanding (observing an action is said to map directly onto the observer’s motor system, thereby allowing action understanding). Additionally, mirror systems have been implicated in imitation (Iacoboni et al., 1999), speech processing (Rizzolatti & Craighero, 2004), empathy (Gallese, 2005), all the way to cigarette addiction (Pineda & Oberman, 2006). Mirror neurons appeared to be a panacea for psychology and neuroscience. However, the ballyhoo has given way to tentativeness. A recent

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However, the link between perception of speech and articulatory gestures does not necessarily mean that speech is special (e.g., Fowler 1986).

<sup>2</sup> An oft-cited Gibsonian aphorism summarizing the non-representational nature of ecological psychology is: “It’s not what’s in the head that is important, it’s what the head is inside of.”



paper by Turella and colleagues (2009) argued for the relative lack of evidence for mirror systems in humans since their discovery 13 years ago in macaques. However, they conveniently excluded many supporting studies that were not directly comparable to mirror neuron studies with monkeys (e.g., Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005). While mirror systems may not solve all neuroscience's questions, the overall evidence for overlapping perception-action systems remains strong.

### 1.3. Sensorimotor Synchronization

Sensorimotor synchronization “in the wild” can be a very complex task that often includes coordinating multiple joints of multiple limbs with many external pacing sequences that are variably timed and occur in multiple modalities. A drummer, for example, can precisely synchronize different movement patterns in four limbs along with the sounds and movements of the rhythm section, while holding back the rushing trumpet player and ignoring the arrhythmic audience claps. Such an impressive feat of perception, action, cognition, volition, and timing eludes a comprehensive methodology.

In the most constrained laboratory setting, SMS experiments use a single finger tapping in a 1:1 frequency relation with a simple referent pacing sequence. Experiments vary additional parameters such as: the number of fingers, limbs, or people tapping; the rhythmic complexity; the rates or the temporal variability of the referent sequence; stimulus modality; the addition of a distractor task; etc. Common dependent variables in these studies include the magnitude and variability of tap-to-target asynchrony (a measure of how participants synchronized with the referent sequence) and the magnitude and variability of inter-tap-intervals (a measure of

tapping tempo and consistency). These measures can be calculated using linear or circular treatments of the data (see the Appendix for a primer on circular statistical methods). Results from the wealth of studies on SMS point to a complex story that lacks consensus on some key theoretical issues.

### 1.3.1. Tap Timing and the Negative Mean Asynchrony

When participants tap along with an isochronous referent sequence, their taps typically precede targets by 30-80 ms. This anticipation tendency or negative mean asynchrony (NMA) has been observed in many studies. Participants are generally not aware of their tendency to tap before the beat, suggesting subjective simultaneity of slightly asynchronous taps and targets. The NMA decreases when the target's "perceptual center" is delayed (i.e., by lengthening the target's duration, or shortening its rise time; Vos, Mates, & von Kruysbergen, 1995), and also when explicit auditory feedback is added to taps (Aschersleben & Prinz, 1995). The NMA also decreases for participants with extensive musical experience (Aschersleben, 2002), as well as when tapping with more musically complex patterns (Snyder & Krumhansl, 2001), or when the target sequences are subdivided (Wohlschläger & Koch, 2000). Additionally the NMA decreases with faster tempi (e.g., Kolers & Brewster, 1985).

Many theories have been proposed to explain tap timing and the intricacies of the negative mean asynchrony. However, none of these theories fully predict the behavioral results, and the exact causes remain clouded (Repp, 2005). I will briefly discuss four leading theoretical explanations.

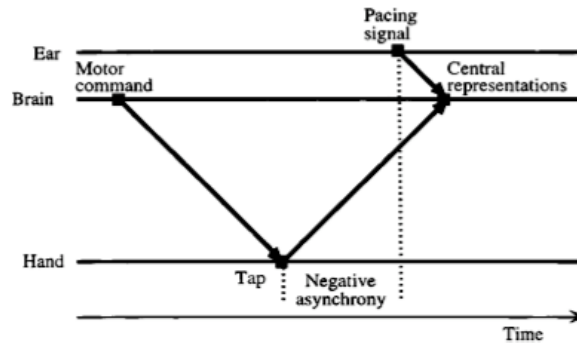
The *nerve-conduction hypothesis* suggests that because neural transmission times to the brain are longer for tactile information (from the tap) than for auditory information (from the pacing signal), the tap must precede the target tone in order to

establish simultaneity at a central level (Aschersleben & Prinz, 1997; Fraisse, 1980; see Figure 1.2). The nerve-conduction hypothesis stresses the role of peripheral processes. This theory accounts for the general NMA and additionally is supported by evidence for a larger NMA when tapping with the foot than when tapping with the hand (Aschersleben & Prinz, 1995). The addition of auditory feedback to taps decreases the NMA, as would be expected if the sensory feedback from the tap's auditory component (fast transmission) holds more weight than the tactile component (slow transmission) when being aligned with the perceived timing of the target. Similarly, musicians likely rely more on the auditory feedback of their movements than non-musicians, who may rely more on the tactile feedback (Repp, 2005); thus musicians calibrate their movement timing based on auditory perceptual effects. The nerve conduction hypothesis does not account for smaller NMAs at faster tempi.

The *sensory accumulator hypothesis* is also based on the notion that simultaneity is established at a central level and that the tap is encoded in terms of its perceptual effect (as postulated by the common coding theory). However, this hypothesis postulates that the time of occurrence of an event is not passively derived from the arrival time of the afferent neural code as in the neural conduction theory; rather it is actively computed based on the features of the incoming signal such as density, intensity, and duration. The sensory representation must accumulate centrally and reach a critical threshold for it to be experienced as one neural entity (Aschersleben, 2002). The importance of the *perceived* time of an event relates closely to perceptual centers as proposed in the area of speech perception (Morton, Marcus, & Frankish, 1976). The sensory accumulator hypothesis accounts for the NMA if tactile information accumulates more slowly than auditory information. Larger NMA when tapping with the foot can be accounted for by the less dense receptors in the toe than

the finger. Also, it might account for effects of tempo: faster tapping presumably yields more tactile information (Aschersleben, 2002).

a. The nerve conduction hypothesis



b. The sensory accumulator hypothesis

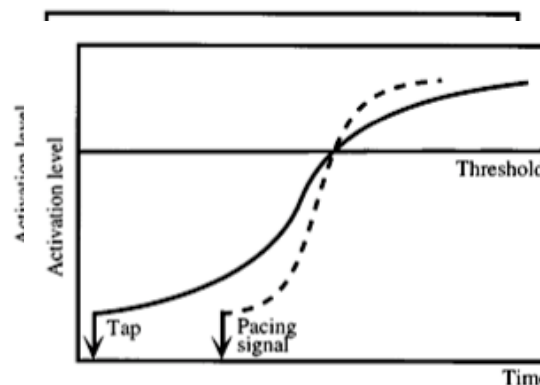


Figure 1.2. Schematics representing a) the nerve conduction hypothesis and b) the sensory accumulator hypothesis (see text for details; adapted from Aschersleben, 2002).

Another theory that can account for tempo effects on the NMA is a *perceptual underestimation* theory proposed by Wohlschläger and Koch (2000). When targets are separated by empty spaces, the targets are commonly perceived as occurring closer in time than they actually occur (e.g., Thomas & Brown, 1974). This perceptual

underestimation would cause taps to precede the empty interval targets. The underestimation is proportional to the inter-onset-interval (IOI), and thus decreases at faster tempi. Simply filling the interval between targets with stimulus subdivisions or random noise “raindrops,” or filling the interval between taps with a contact-free tap, reduces the NMA.

Finally, a *dynamical systems* account can also predict the tap timing and the NMA. Such a treatment views the system as a series of coupled oscillators: the driven oscillator is the tap and the driving oscillator is the auditory pulse. Eigenfrequency mismatch between oscillators leads to phase lag with the inherently faster oscillator (the finger in this case) preceding the slower oscillator (the target metronome) (Pikovsky, Rosenblum, & Kurths, 2001). As the target frequency increases, the mismatch decreases, along with the NMA.

None of these theories are mutually exclusive, and a comprehensive understanding of the NMA might need to integrate pieces of multiple theories (Repp, 2005). The sensory accumulator hypothesis is appealing – actions are coded in terms of their perceptual effects, and simultaneity occurs at a central, subjective level rather than an objective physical level. However, it does not account for smaller NMAs when subdividing the IOI; whereas perceptual underestimation nicely explains this effect. Regarding the overall NMA, however, consistent perceptual underestimation seems very implausible – the system should soon recalibrate the temporal aspects to mitigate any perception-action discrepancy (cf. Haggard, Clark, & Kalogeras, 2002; and Stetson, Cui, Montague, & Eagleman, 2006; for evidence for the flexible and fast temporal recalibration between perception and action systems). A dynamical systems perspective might provide a plausible model for the continuous processing and sensorimotor integration that occurs “under the hood.” However, at a higher explanatory level, discrete finger taps can be captured fairly successfully with discrete,

stage-based information-processing accounts, and therefore have been popular (Repp, 2005). Pressing (1999) made an important initial step to bridge dynamical systems and information-processing perspectives. Combining stage-based information-processing accounts that typically deal with discrete tapping data and continuous dynamical approaches that typically deal with movement trajectories seems to be a fruitful avenue for understanding how the nervous system times repetitive movements (Balasubramaniam, 2006). My planned future work employing motion-capture methods in finger tapping experiments with various auditory and visual stimuli could contribute to building this theoretical bridge between information-processing and dynamical systems approaches.

In the current context, a method of contrasting the nerve conduction hypothesis with the sensory accumulator hypothesis would be to compare the NMA when tapping with two-note chords that either contain small onset asynchronies or no asynchrony: Would motor timing be based simply on the first spikes received from the auditory system (consistent with a peripheral nerve conduction account), or would it be based on a perceptual center of chords (consistent with a central sensory accumulator account)? Chapter 2 examines this question and shows that the NMA is indeed based on the perceptual center of the chords; however, participants consistently tapped 40-50 ms before the perceptual center and this could in part arise from peripheral nerve conduction times.

Similarly, one could test these hypotheses in visuomotor synchronization by comparing tapping with sequences of dim vs. bright flashes. Processing latencies for dim flashes are approximately 80 ms longer than for bright flashes (Purushothaman, Patel, Bedell, & Ogmen, 1998): Would people tap later for dim flashes as the sensory accumulator hypothesis predicts, or would the motor system work off the first spikes (nerve conduction)?

Finally, another potentially fruitful avenue for research could combine visuomotor synchronization with the flash-lag effect literature. The flash-lag effect shows that a flash is wrongly perceived to lag behind a predictably moving object when the object is in the same coordinate position at the time of the flash (Nijhawan, 1994, 2002). Potential explanations include: 1) perception is predictive, thus the perceptual system extrapolates future movement for the moving object, as in the phenomenon of representational momentum (Nijhawan, 2002; Wilson & Knoblich, 2005); 2) perception is *postdictive*, thus incoming signals are interpreted/reconstructed within 80 ms after the flash (Eagleman & Sejnowski, 2000); or 3) processing times are a function of luminance, thus if the luminance of the flash is increased its processing time is faster and the effect disappears (Purushothaman, Patel, Bedell, Ogmen, 1998). Testing flash-lag as a perceptual-motor task, rather than simply a perceptual phenomenon, with the right stimuli (fast vs. slow movement, bright vs. dim flashes, apparent vs. real motion) could contribute to understanding the flash-lag effect.

### 1.3.2. Tapping Variability and Error Correction

Tapping variability is an important and informative measure of tapping performance, where the standard deviation (SD) of asynchrony and circular variance pertain to synchronization success, and the SD of inter-tap interval (ITI) pertains to tempo variability. The SD of ITI is typically around 3-5% of the ITI in practiced participants (e.g., Semjen, Schulze, & Vorberg, 2000). Thus, variability, when quantified as SD, decreases at faster tempi. However, another common measure of variability, the coefficient of variation (SD of ITI divided by ITI), accounts for tempo dependency and is relatively constant across tempi (and is roughly consistent with Weber's law). Tapping variability can decrease with musical training and trained

percussionists' SD of ITIs can be as low as 0.5% of the tempo (2.5 ms at 500 ms IOI) (Gerard & Rosenfeld, 1995; Repp, 2005).

In self-paced tapping, the variability of tapping has been attributed to two component sources: an internal timing mechanism and delays in motor implementation (Wing & Kristofferson, 1973). This highly influential model assumes that a central timer provides the interval timing and triggers a motor command. Variance associated with motor implementation is relatively small and varies little based on tempo, compared to timekeeper variance, which is larger at slow tempi. Wing and Kristofferson's open loop model has been used widely and is generally well supported. The two separate sources of variability nicely predict dependence patterns between successive intervals in self-paced tapping. Lag-1 autocorrelations are negative, meaning if one ITI is long, the subsequent ITI will tend to be short. This negative lag-1 autocorrelation can be attributed to variable delays in the system (a long efferent delay for completing one ITI will tend to shorten the next ITI and vice versa), rather than arising from an additional layer of feedback and error correction (which would also yield a negative lag-1 autocorrelation).

Wing and Kristofferson's model has been extended from self-paced tapping to synchronized tapping with an external pulse (e.g., Vorberg & Wing, 1996). Models of synchronization typically contain an error correction term that tracks the synchronization error between tap and target and accordingly adjusts tap timing. This error correction mitigates phase drift and keeps tapping synchronized to the referent pulse; however, the adjustments have an associated "cost" of slightly increased ITI variability (Semjen, Schulze, & Vorberg, 2000). A number of researchers (e.g., Mates, 1994a; Schulze & Vorberg, 2002) suggest that the asynchrony must exceed a certain threshold before error correction mechanisms are engaged (although error correction occurs for timing perturbations that are not consciously detected, Repp,



2001). Most existing error correction models do not include a threshold, an exception being Mates's (1994a, 1994b) model. In the experiments described in Chapter 2, participants synchronized with auditory chords containing nonsimultaneous onsets, which decreased tapping variability for musically trained participants relative to simultaneous onset chords. These multiple proximal onsets may have enlarged the span of time over which deviations are too small to engage error correction mechanisms. In other words, when there are two onsets, the likelihood of "being on the beat" increases, so phase correction responses would be less active and ITI variance would decline.

Wing & Kristofferson's model and most subsequent synchronization models that adopt an information processing perspective rely on a central timekeeper or clock mechanism. This basic tenet, however, is controversial and other research suggests that timing emerges from nonlinear coupled oscillators, rather than clocking mechanisms (e.g., Schöner & Kelso, 1988). The nature of temporal representations is one of the least well-understood areas in neuroscience (Ivry & Spencer, 2004). A theoretical dichotomy exists between general, localized time-dedicated clock systems versus a more distributed, task-specific representation of time. The compatible motion effects in synchronization to be demonstrated in Chapter 3 seem to support action-oriented representations of temporal information, rather than an isolated clock mechanism.

Finally, as dependencies between taps can be informative, tap dependencies were calculated for the interpersonal synchronization experiments presented in Chapter 4. Correlations between the experimenter and participants were analyzed at various lags. Significant correlations at lag  $\pm 1$  would suggest that one member of the dyad disproportionately influenced the other member's actions. However, such significant correlations were not observed. This might reflect the nature of the task – tappers

were instructed to synchronize with the visual metronome, not the other person. Future research on interpersonal synchronization could yield informative lag  $\pm 1$  correlations by encouraging interpersonal synchrony, lengthening trials, or manipulating social status (Would the subordinate person tend to follow? Would a participant primed to take a more dominant role and be impervious to the actions of the tapping partner?).

### 1.3.3. Modality Effects in Sensorimotor Synchronization

Large differences exist between modalities in SMS. A wide range of experiments reveals that visuomotor synchrony is much worse than auditory-motor synchrony (e.g., Chen, Repp, & Patel, 2002), with tactile-motor synchrony intermediate (Kolars & Brewster, 1985). Successful synchronization is possible at much faster rates with isochronous auditory stimuli than with isochronous visual stimuli (Repp, 2003). Additionally, participants can synchronize with non-isochronous metrical rhythms in the auditory modality, but not the visual modality (Patel, Iversen, Chen, & Repp, 2005). In a target-distractor paradigm that varies the relative phase between auditory and visual stimuli, taps are strongly attracted to auditory distractors, whereas visual distractors are easily ignored (Repp & Penel, 2002, 2004).

The observed auditory advantages reflect differences in sensorimotor integration and/or differences in the perceptual processing. The vast majority of visuomotor experiments use flashing stimuli, despite the visual system's known proclivity for processing spatial variation over purely temporal variation. The use of spatial variation (translation over time) might dramatically improve visuomotor synchronization (Repp & Penel, 2004). Chapter 3 explores this question, and shows that moving visual stimuli (especially when compatible with finger movement) do in fact yield improved performance, which suggests tight perception-action links.

However, auditory-motor synchronization performance remained much better than visuomotor synchronization even with compatibly moving stimuli.

In light of vast improvements in visuomotor synchronization with compatibly moving stimuli, a follow-up experiment should use compatible motion in Repp and Penel's (2002, 2004) multimodal target-distractor paradigm.<sup>3</sup> Will tap timing still be dominated by the auditory modality, or will tap timing be based on a multimodal weighted average of auditory and visual sequences? In the McGurk effect, for example, moving visual information is weighed against auditory information (McGurk & MacDonald, 1976). This experiment would elucidate both sensorimotor and multimodal integration.

#### 1.4. Perception-Action Links in Social Cognition

The tendency to imitate or mimic others is widespread and relies on tight perception-action linkages (e.g., Iacoboni et al., 1999). Perceiving an action activates the mental representation for that action (e.g., Decety & Grèzes, 1999), making that

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<sup>3</sup> From a technical perspective, reliable timing for both auditory and visual stimulus presentation necessary for this experiment is possible with Matlab's psychtoolbox 3, a fast video card, and an external CRT monitor. I ran into a few issues and hurdles with other programs and configurations along the way.

action more likely.<sup>4</sup> Mimicry has been shown to lead to affiliation or likeability between people, and perception-action links have been proposed to drive this effect (Chartrand & Bargh, 1999; Dijksterhuis & Bargh, 2001). Overlapping representations for perception and action naturally extend to overlapping representations of self and other, a potentially important factor for affiliation, empathy, and social bonding (Gallese, 2003; Hurley, 2008).

The tendency to synchronize with others is well established. The same coordination dynamics that exist *within* an individual (e.g., the unintended propensity for fingers to fall into synchrony; Kelso, 1995) also exist *between* individuals. When seated next to each other, participants' swinging legs unintentionally come into phase with each other (Schmidt, Carello, & Turvey, 1990). Bodies sway in synchrony (Shockley, Baker, Richardson, & Fowler, 2007) and people in rocking chairs rock into phase with each other (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007). A recent EEG experiment provided evidence for perception-action involvement in interpersonal synchrony (Tognoli, Lagarde, DeGuzman, & Kelso, 2007). In this interpersonal finger-tapping study, two EEG oscillatory components, whose topographies were consistent with the mirror system, distinguished coordinated from

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<sup>4</sup> Action observation does not necessarily lead to imitation. Imitation is usually carried out covertly (i.e., simulation), rather than overtly (Wilson & Knoblich, 2005). Frontal lobe inhibitory mechanisms have been postulated to inhibit overt imitation, and develop during childhood (children tend to overtly copy more than adults; Hurley, 2008). Thus, while shared perception-action codes provide a likely mechanism underlying overt imitation, the perception-action links are typically inhibited or moderated (otherwise, we would constantly 'ape' everyone).

uncoordinated tapping. The authors suggest that the EEG component during phase-locked coordination could be associated with mirror system *enhancement*, whereas the component during uncoordinated tapping could be associated with mirror system *inhibition*.

Chapter 4 explores the effect of interpersonal synchrony on affiliation. If mimicry leads to affiliation due to representational overlap of perception-action and self-other, synchrony should yield even stronger affiliative effects because the representational overlap is greater when incorporating temporal alignment. Results in Chapter 4 substantiate this hypothesis.

### 1.5. Perception-Action links, Movement Induction, and Music

The tight linkages between perception and action can lead to automatic induction of movement. Similar to mimicry, simply perceiving an action can spontaneously induce that same movement. In addition to this involuntary, automatic imitation, movement induction can also be goal-directed: Spontaneous movements sometimes reflect what observers *want to* occur (e.g., when watching sports on TV and trying to coerce the ball in the hoop/hole/bleachers); this suggests that goals play a role in the “representational resources shared between perception and action” (Prinz, Aschersleben, & Koch, 2009). However, in this context I will concentrate on movement induction resulting from lower-level, more direct perception-action links. Music provides an informative model system.

Effects of perception-action linkages can be observed in movement induction in musicians and have been shown to develop with training. After years of training and strengthening sensorimotor coupling, musicians often report that simply hearing music can lead to involuntary correlated movements. When listening to piano music,

pianists, but not non-pianists, showed heightened contralateral motor cortex activation (Haueisen & Knösche, 2001). In another study, EEG patterns of participants were monitored while they practiced a new piano piece and while they simply listened to the piece. As performance improved, EEG patterns during listening and during production became increasingly similar, indicating that perception-action couplings in skilled movement develop with training (Bangert, Parlitz, & Altenmüller, 1999).

Additionally, pianists can consistently identify recordings of their own playing, even when all cues other than expressive timing and articulation are removed. This study suggests that self-recognition relies on common coding: The observer's action system is activated most strongly by perceptions of self-produced actions (Repp & Knoblich, 2004). In a joint-action extension of this work, Keller, Knoblich, and Repp (2007) showed that pianists synchronize most precisely with recordings of themselves. Synchronization requires predictive simulation of others' actions. Presumably, the predictive simulations were more accurate for self-generated performance because they were carried out by the same perception-action system; hearing yourself resonates most with your own action system.

Music is inextricably linked to movement. Theorists often forget or ignore the fact that sound is generated by a performer's actual movements: "Music movement is, among other things, *human* movement" (Shove & Repp, 1995). The degree of movement in music is sometimes called the music's 'groove.' Specifically, groove refers to movement induction – how the music literally moves us (Iyer, 2002; Janata, 2007). Pressing (2002) proposed that groove is a temporal phenomenon emerging from carefully aligned rhythmic patterns characterized by: 1) recurring pulses; 2) cyclic structure; and 3) effectiveness in engaging synchronized body responses (e.g., dance, foot-tapping).

The main inspiration behind the experiments in Chapter 2 comes from the concepts of movement induction and groove. A common component of groove is that rhythm section players purposefully play slightly apart from each other in time (e.g., the bass onsets consistently precede drum onsets by 30-50 ms). The purpose of these onset asynchronies could be to decrease auditory masking associated with strict simultaneity; to indicate a collective social event (Iyer, 2002; Keil, 2002); and/or to express musical movement (each beat unfolds over time like movement; cf. Shove & Repp, 1995). The Chapter 2 result of more regular tapping with multiple onset chords suggests a link between the motor system and onset asynchronies common to groove music.

An additional result in Chapter 2 shows that movement timing was determined more strongly by low-pitched tones, than high-pitched tones. Similar effects of low-pitched tones have been observed previously (e.g., Handel & Lawson, 1983; and Repp, 2003), but have not yet been systematically investigated. Low tones might affect movement timing more due to a purely auditory “upward spread of masking” (i.e. low tones mask high tones more than vice versa, Moore, 1997). However the high tones in the Chapter 2 experiments were easily perceivable, discounting this purely auditory explanation. An alternative account intimates a cross-modal system that favors a connection between low tones and physical movements. Low tones can yield increased somatosensory stimulation, which can affect auditory cortex (Fu et al., 2003), and low, loud sounds have been shown to evoke a vestibular response that may induce movement (Todd, 2001).

## 1.6. Dissertation Outline

Chapter 1 reviewed theoretical background relevant to sensorimotor synchronization, including the negative mean asynchrony, error correction, and sources of variability. It discussed perception-action links in terms of common-coding and mirror neuron systems, how these perception-action links apply to sensorimotor synchronization, and how they might extend to social cognition and understanding others' actions.

Chapter 2 presents three experiments investigating SMS in the auditory domain. Ensemble music performance requires synchronizing movements to multiple tones with multiple onsets. This task was simulated with finger-tapping to a sequence of two-tone chords containing small onset asynchronies (25-50 ms) or containing simultaneous onsets. We additionally measured each chord's perceptual center in order to compare perceptual and motor timing.

Chapter 3 presents two experiments investigating SMS in the visual domain. Previous research has indicated poor performance in visuomotor synchrony with flashing stimuli. However, since the visual system is more adept at processing spatial information than solely temporal information, moving stimuli might facilitate synchronization performance. The second experiment investigates the degree of directional compatibility between the stimulus and finger movement. The third experiment compares synchronization performance for auditory vs. visual stimuli.

Chapter 4 presents three experiments on interpersonal synchrony and its effects on affiliation. Synchronization in ensemble music or coupled dancing seems to promote affiliation. In a series of interpersonal synchronization experiments, participants matched their movements to a moving visual metronome, while an experimenter sitting within view tapped to her own metronome that was either in time with the



participant's metronome, at a different rate, or did not tap. The third experiment explored whether tapping with an inanimate metronome (synchronous or asynchronous) affected affiliation ratings for the experimenter.

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## CHAPTER 2

### SENSORIMOTOR SYNCHRONIZATION WITH CHORDS CONTAINING TONE- ONSET ASYNCHONIES<sup>5</sup>

#### Abstract

Musical ensemble performance requires the synchronization of multiple performers, resulting in sequences of chords containing multiple tones with multiple onsets. Experiments 1 and 2 investigate whether sensorimotor synchronization with chord sequences containing tone-onset asynchronies is affected by (1) the magnitude of these asynchronies (25, 30, or 50 ms) and (2) the pitch of the leading tone (high vs. low). Participants tapped a finger in synchrony with different types of chord sequences created by crossing these variables, as well as with sequences of chords containing simultaneous onsets. Results indicate that taps were drawn toward the second onset, when present, especially when it was lower in pitch than the first. Additionally, chords with nonsimultaneous onsets increased tapping variability for nonmusicians, but decreased variability for musicians. Experiment 3 measured the perceptual centers of the chords from Experiment 2, and yielded results suggesting that subjective onsets determine the temporal placement of taps during synchronization.

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<sup>5</sup> Hove, M. J., Keller, P. E., & Krumhansl, C. L. (2007). Sensorimotor synchronization with chords containing tone-onset asynchronies. *Perception and Psychophysics*, 69, 699-708. Copyright © 2007 by the Psychonomic Society. Adapted with permission.

## Introduction

The synchronization of rhythmic movements with auditory sequences is a key aspect of skilled musical performance. Musicians routinely synchronize their actions with chords containing multiple component tones. For example, a soloist must synchronize with chords of a piano accompaniment, or with different voices in an orchestra or jazz rhythm section. In the context of live human performance, the onsets of these multiple components are typically not in perfect temporal synchrony. The experiments reported here investigate the effect that asynchronous tone onsets have on tap timing accuracy and variability during sensorimotor synchronization.

Asynchronous onsets of musical tones are common and arise from various sources. At the most basic level, asynchronies reflect limitations in synchronization accuracy that stem from perceptual, cognitive, and motor implementation constraints. Due to these limitations, consistently perfect synchrony is not possible. Musical training, however, greatly decreases error and variability in synchronization (e.g., Gérard & Rosenfeld, 1995; Pressing & Jolley-Rogers, 1997; Repp & Penel, 2002).

Nevertheless, highly trained expert musicians often intentionally produce asynchronous onsets between nominally simultaneous notes in both solo and ensemble music. Analyses of timing in solo piano performance reveal that the melody note often precedes other voices by 20–50 ms, thereby increasing the perceptual salience of the melody line (Palmer, 1996); or it may be, at least in part, a velocity artifact of louder dynamics (Goebel, 2001; Repp, 1996). Some pianists systematically lead with low tones, and this represents a deliberate, expressive strategy (Repp, 1996). Asynchronies produced for expressive purposes are also common in ensemble performance. For example, Rasch (1988) examined the respective note onsets of string trio players and found the violin's lead voice preceded the cello by 5–10 ms on average, which preceded the viola by another 5–10 ms. Purposeful and systematic

onset asynchronies have also been studied in the context of jazz and popular music, where they are thought to be a key factor in the somewhat nebulous musical concepts of “groove,” “feel,” and “swing” (Collier & Collier, 1997; Friberg & Sundström, 2002; Iyer, 2002; Keil, 1995). Timing analyses of an Afro-Cuban percussion ensemble showed that the lead drum tended to play 30 ms ahead of the *clave*, a reference percussion instrument (Bilmes, 1993). Other examples include the bass lead in James Brown’s band, the “wide beat” of the Miles Davis Quintet of the 1960s, the RZA’s nonquantized hip-hop grooves, and even some of the orchestral works of Brahms.<sup>6</sup>

Despite their widespread presence in music, onset asynchronies are often not consciously perceived by listeners. A wide pitch difference between asynchronous tones, and different timbres and rise times, contribute to onset asynchronies passing unnoticed. In addition, attention may be drawn more to the “horizontal” timing of one melody line than to the “vertical” relations between simultaneous lines (Rasch, 1988).

However, psychophysical experiments have shown that onset asynchronies are easily perceived under carefully controlled laboratory conditions. Approximately 20 ms is sufficient to discern the temporal order of two asynchronous sounds for highly trained listeners (Hirsh, 1959); untrained listeners may need much longer time intervals (Broadbent & Ladefoged, 1959). In sensorimotor synchronization

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<sup>6</sup> For example, in the first movement of Brahms’s Piano Concerto No. 1, the composer enhances the salience of a structurally important location in the music by requiring the basses to sound on the final beat of one bar (i.e., an upbeat), followed by a dissonant chord in the rest of the ensemble on the first beat of the next bar. This ensemble bass lead reflects Brahms’s expressive left hand lead, heard in the Edison cylinder recording of his piano performance of the Hungarian Dances (Bellman, 2003).

experiments, displacing a pacing sequence event by less than 20 ms from its putatively expected time may not be consciously detected in perception, but nevertheless may elicit compensatory changes in tap timing (Repp, 2001, 2002). Larger values can affect the perceptual organization of musical textures. Specifically, it has been shown that tone sequences temporally offset by about 30 ms or more tend to be perceived as separate streams, if the frequency difference between tones is sufficiently large (Bregman & Pinker, 1978).

The existence of systematic onset asynchronies in music, together with the results from the psychophysical literature, raise the question of whether these asynchronies affect sensorimotor synchronization with the perceived beat (i.e., the most salient level of pulsation experienced when listening to music). Specifically, is the temporal goal for synchronization based solely on the first onset within a chord complex, on the average of all onsets, or on some other form of temporal derivative such as the perceptual center (Vos, Mates, & van Kruysbergen, 1995) of the chord? Furthermore, given that the presence of multiple tone onsets within a chord creates the potential for multiple synchronization targets, is movement timing variability increased under such circumstances?

The literature on sensorimotor synchronization dates back over 120 years (for a recent review, see Repp, 2005). Experiments generally consist of synchronizing a movement, often a finger tap, with an external metronome. Typical dependent variables in such experiments are mean tap-to-metronome asynchrony and mean intertap interval (ITI) and the variability of both measures. Recently, researchers have started to investigate sensorimotor synchronization with more musically relevant stimuli (Large, 2000; Repp, 1999; Snyder & Krumhansl, 2001). Nevertheless, studies that address issues related to the effects of onset asynchronies on sensorimotor synchronization remain rare, with the exception of recent work by Repp (2003, 2004).

Repp (2003, 2004) instructed his participants to tap in synchrony with the tones of a “target” sequence while ignoring an interleaved “distractor” sequence that either lagged behind or anticipated the target sequence by varying amounts. The target sequence was presented for a while before its accompanying distractor sequence began. Target and distractor sequences differed in pitch by 3–20 semitones, and ranged from 1976 Hz to 4192 Hz, depending on experiment. Repp (2003, 2004) found that participants had difficulty ignoring the distractors when they occurred within 100–150 ms of the targets. Such distractors drew taps away from the target sequence, particularly when they preceded the target tones, and increased tap timing variability. The effects of the distractors being higher or lower in pitch than the targets were inconsistent, and for a few reasons it is unclear how these findings relate to the effects of onset asynchronies in musical performance. First, in most instances of ensemble performance, musicians are required to attend to other instrumental parts rather than to ignore them. Second, the target and distractor tones used by Repp (2003, 2004) were high in frequency and out of the typical pitch range of rhythm-setting musical instruments.

This article presents three experiments. Experiments 1 and 2 investigate whether sensorimotor synchronization with chord sequences containing tone-onset asynchronies is affected by (1) the magnitude of these asynchronies and (2) the pitch of the leading tone. Control sequences composed of chords with simultaneously sounding tone onsets were also employed. To simulate partially the demands of synchronization during musical ensemble performance, participants were simply instructed to synchronize “with the beat” rather than with just one specific component of the chord, and the lowest tone (350 Hz) in the chords was close to the center of the typical musical pitch range. The effects of musical experience on synchronization under these conditions were assessed by testing people with various amounts of

musical training. Note that tone-onset asynchrony was held constant from chord to chord within a sequence, whereas in musical performance asynchronies naturally fluctuate from chord to chord. We opted to hold tone-onset asynchrony constant for reasons of experimental control; otherwise, chord sequences with simultaneous and nonsimultaneous onsets would vary not only in terms of relative tone-onset times, but also in terms of whether onset times varied from chord to chord within a sequence. Experiment 3 examines the perceived onset time, or perceptual center (P-center), of chords containing onset asynchronies in order to assess whether tap timing in the first two experiments was based on P-centers rather than on physical event onsets.

### Experiment 1

The purpose of Experiment 1 was to investigate whether tone-onset asynchronies affect sensorimotor synchronization. Toward this end, a sequence of two-tone chords was presented in which a low tone slightly preceded a high tone. In a control condition, two-tone chords in which the onsets were synchronous were used. Four dependent measures were used as indices of performance accuracy: mean tap-to-chord asynchronies, variability (standard deviation) of asynchronies within a trial, mean ITIs, and within-trial ITI variability. For simplicity in analysis, the first tone onset of a chord was considered to be the chord onset. Indeed, if a chord is perceived as a single event despite the presence of onset asynchronies, the onset of the first tones is the physical onset of this event. Asynchronies are each based on the timing of a single tap relative to an event in the pacing signal, whereas ITIs are based on the timing of two adjacent taps independently of the pacing signal. Thus, asynchronies provide an index of the phase relationship between taps and the pacing sequence, whereas ITIs are a measure of tapping period, or tempo.

#### *Method*



### *Participants.*

Fifteen adult, unpaid volunteers (10 women, 5 men; age range, 22–33 years; mean age, 27.1), including authors M.J.H. and P.E.K., participated in Experiment 1. All participants were right-handed, as assessed by self-report. Total years of musical performance experience ranged from 0 to 20 years ( $M = 8.2$  years). Eight participants, hereafter referred to as “musicians,” had more than 6 years of formal musical training and ensemble experience. The remaining participants were designated “nonmusicians.”

### *Materials.*

The chords used in the stimulus sequences were composed of two sine tones: a short 50-ms high tone (1400 Hz) and a slightly longer 80-ms low tone (350 Hz). The high tone was 2 octaves above the low tone. The tones were generated with CoolEdit software, equated for loudness, and were combined in two different types of chords: (1) the low-tone onset preceded the high-tone onset by 30 ms, so the tones ended together; or (2) both tone onsets were presented simultaneously, so the 80-ms low tone ended 30 ms after the 50-ms high tone. This resulted in chords with two segments, one in which only a single tone sounded, and another in which two tones sounded. After superimposing the high and low tones, the amplitude of the single-tone segment (at either the onset or the offset) was adjusted so that it and the two-tone segment had equal maximum amplitude levels (60 dB under our presentation conditions). Thus, the two segments of the chord differed in frequency content, but not in amplitude. This amplitude equalization allowed investigation of effects of pitch on synchronization while minimizing any confounding effect of different amplitude. Despite being less natural, the amplitude change within the longer tone was imperceptible and the chords still sounded pleasant and musical to authors M.J.H. and P.E.K. Each trial consisted of a single chord presented 20 times successively with a

stimulus interonset interval (IOI) of 500 ms. The 500-ms IOI reflects the time between the first occurring element in one chord (whether the low tone or simultaneous low 1 high tone) and the first element of the next chord.

#### *Procedure.*

Participants sat in front of a computer monitor that displayed the trial number, and listened to the sequences over PRO-10 isolation headphones. They tapped with their right index fingers on a 3 x 3 cm metal plate that produced no sound audible through the headphones. The sequence was presented and taps were recorded via Experimental Run Time System (accurate to 1 ms). Participants were instructed to start tapping with the 3rd chord and to tap in synchrony with “the beat.” The presence of high and low tones and their onset/offset difference was not mentioned in the instructions. The experiment consisted of 4 blocks of 12 randomized trials (6 of each of the two chord types per block). The first 2 trials of each block (one for each chord type) were not analyzed, so of the 48 total trials, 40 were analyzed. Trials were initiated by the participants, and short breaks were included after each block. The entire experiment lasted approximately 20 min.

#### *Results and Discussion*

It typically took a few cycles for synchronization to stabilize at the beginning of a trial, and therefore only taps corresponding to chords 7–19 (taps 5–17) were analyzed; our analysis therefore focused exclusively on asymptotic performance from the trials. Within-trial standard deviations of tap-to-chord asynchronies were screened for outliers. Of the 600 total trials, 9 trials yielded greater than 2.5 times an individual’s average standard deviation and were excluded from the analyses. Average data for mean asynchronies, *SD* of asynchronies, mean ITIs, and *SD* of ITIs are shown in Table 2.1. These data were entered into separate ANOVAs with the within-participants factor chord type (simultaneous vs. nonsimultaneous) and the between-participants

factor musical experience (musician vs. nonmusician). The criterion for statistical significance was set at  $\alpha < .05$  for all analyses reported in this article.<sup>7</sup>

Table 2.1. *Mean Asynchrony, Within-Trial SD of Asynchronies, Mean Inter-Tap Interval (ITI), and Within-Trial SD of ITIs Averaged Across Musicians and Non-musicians from Experiment 1.*

Measure	Chord type	
	Simultaneous onset	Non-simultaneous onset
Mean Asynchrony	-44.35 (36.03)	-40.77 (32.48)
SD of Asynchronies	19.98 (3.77)	20.06 (4.06)
Mean ITI	499.83 (0.88)	500.20 (0.92)
SD of ITIs	24.60 (4.39)	24.47 (5.70)

*Note.* The between-participant SD of scores on each measure is shown in parentheses. All values are in ms.

The tap-to-chord asynchrony was measured from the onset of the first tone (or tones) in such a way that taps that preceded tones resulted in negative asynchrony values. The asynchronies were compared for the two trial types. The anticipation tendency common in finger tapping experiments (e.g., Aschersleben, 2002) was

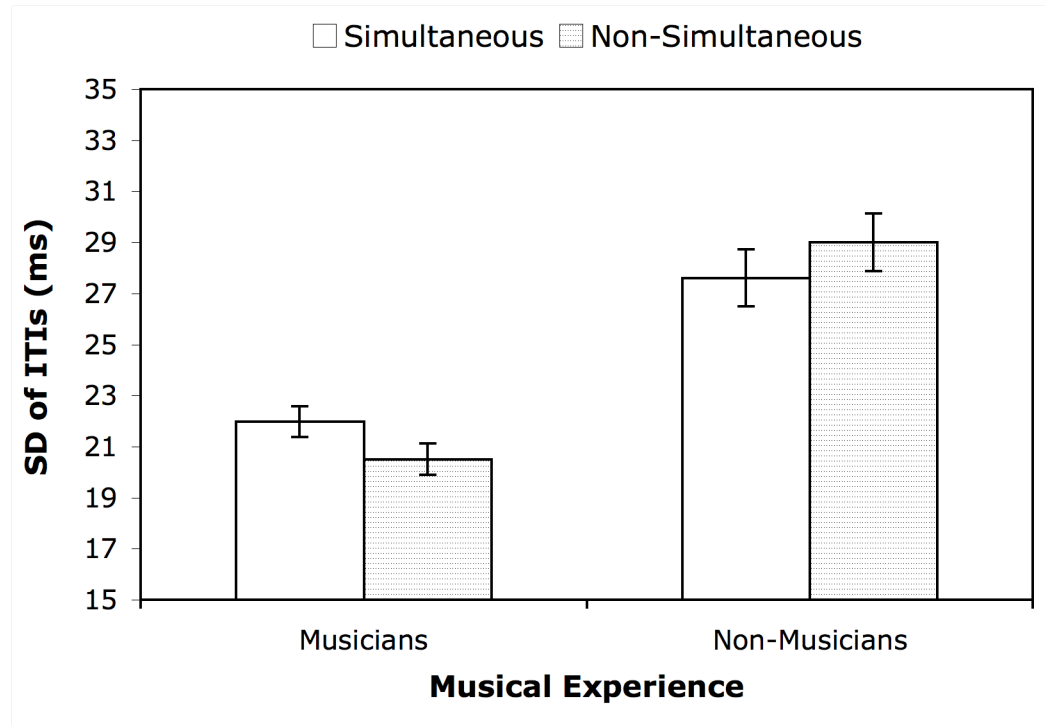
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<sup>7</sup> Analyses on linear statistics and circular statistics yielded the same pattern of results; therefore, only linear statistics are reported.

observed; taps tended to precede chord onsets. Moreover, our analysis revealed that mean tap-to-chord asynchrony for chords containing simultaneous onset of high and low tones was significantly larger (i.e., more negative) than for chords in which the high-tone onset was delayed 30 ms relative to the low-tone onset [ $F(1,13) = 6.02, p < .05$ ]. In other words, the taps tended to occur slightly (~4 ms) later, and nearer to the physical onset of the chord, when the high-tone onset followed the low-tone onset. Neither musical experience nor the interaction of chord type and musical experience affected mean asynchrony reliably ( $ps > .6$ ). Although the placement of taps relative to events in the pacing sequence was affected by chord type, tapping rate was relatively immune to effects of this variable. In fact, participants were, on the whole, highly successful at tapping at the correct tempo: Mean ITI (500.02 ms) was close to the target ITI (500 ms), and was not affected reliably by chord type or musical training or by their interaction ( $ps > .1$ ).

The ANOVAs on our two indices of tap timing variability (*SD* of asynchronies and *SD* of ITIs) revealed comparable results. First, there was no significant main effect of chord type on either measure ( $ps > .6$ ). Second, tap timing variability was generally lower in musicians than in nonmusicians: Average within-trial *SD* of asynchronies was 17.81 ms for musicians and 22.58 ms for nonmusicians [ $F(1,13) = 9.25, p < .01$ ]; average *SD* of ITIs was 21.24 ms for musicians and 28.31 ms for nonmusicians [ $F(1,13) = 16.23, p = .001$ ]. Finally, and most interestingly, there was a significant interaction between chord type and musical experience on both measures: *SD* of asynchronies [ $F(1,13) = 5.51, p < .05$ ]; *SD* of ITIs [ $F(1,13) = 5.34, p < .05$ ]. The results of separate comparisons for musicians and nonmusicians were clearest for the *SD* of ITIs measure, an index of ability to maintain a steady tempo. As shown in Figure 2.1, the *SD* of ITIs was lower with nonsimultaneous onsets than with simultaneous onsets for musicians [ $t(7) = 2.40, p < .05$ ], whereas results are

numerically in the opposite direction for nonmusicians, though this effect was not reliable [ $t(6) = 21.24, p > .2$ ].



*Figure 2.1.* Average within-trial SD of inter-tap-intervals (ITIs) with simultaneous and non-simultaneous onset chords for musicians and non-musicians in Experiment 1. Error bars represent 95% confidence intervals calculated separately for musicians and non-musicians (see Masson & Loftus, 2003).

Overall, the results of this experiment indicate that chords containing tone-onset asynchronies affected tap timing; in particular, taps were drawn toward the second onset. However, the shift was only  $\sim 4$  ms, not the 15-ms shift one might expect if the mean of the two tone onsets (30-ms delay in individual tone onsets) were considered the chord's "onset." This suggests that tap timing is determined

predominantly by the first onset within a chord containing onset asynchronies. Perhaps surprisingly, tapping variability was generally not degraded by the presence of onset asynchronies in the pacing sequence; on the contrary, participants with musical training tapped with less variability when the chords contained nonsimultaneous onsets.

## Experiment 2

The purpose of Experiment 2 was to investigate in more detail the effects on sensorimotor synchronization of the magnitude of tone-onset asynchrony in chords (none, 25 ms, 50 ms) and the pitch of the leading tone (high tone first or low tone first). Thus, participants were required to tap in synchrony with five different types of sequence. Dependent measures were again tap-to-chord asynchrony (as measured from the first tone onset), the *SD* of these asynchronies, mean ITI, and the *SD* of ITIs. On the basis of the results of Experiment 1, we expected that mean asynchrony would be shifted toward the second onset of chords containing onset asynchronies. Whether the amount of shift would be affected by magnitude of tone-onset asynchrony, and whether synchronization would be affected by the order in which the high and low tones occurred within a chord, were questions of interest.

### *Method*

#### *Participants.*

Seventeen adults (12 women, 5 men; age range, 19–31 years; mean age, 24.8) participated in the experiment.<sup>8</sup> Most were students from Ludwig Maximilian University, Munich. All participants were right-handed, as assessed by self-report.

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<sup>8</sup> Data from an 18th participant could not be analyzed because he did not complete the full experimental procedure.

Total musical performance experience ranged from 0 to 20 years ( $M = 10$  years). Seven participants (“musicians”) had more than 6 years of formal musical training and ensemble experience. Participants were previously unfamiliar with the task, and were paid €8 each for participating.

### *Materials.*

As in Experiment 1, each stimulus sequence consisted of chords composed of two sine tones—a high tone (1400 Hz) and a low tone (350 Hz) generated beforehand in CoolEdit and equated for loudness. The tones were combined in five different types of chords: (1) the high-tone onset was followed by the low-tone onset after 50 ms (hereafter denoted as H-50-L); (2) the high-tone onset was followed by the low-tone onset after 25 ms (H-25-L); (3) the high tone and low tone were presented simultaneously (simultaneous); (4) the low-tone onset was followed by the high-tone onset by 25 ms (L-25-H); and (5) the low-tone onset was followed by the high-tone onset by 50 ms (L-50-H). Tone offsets were simultaneous for all chords, and occurred 100 ms after the onset of the first tone. As before, in order to examine the effects of pitch without confounding amplitude information, the amplitude (dB levels) of the individual tone component was adjusted so that it and the chord component had equal maximum dB levels.

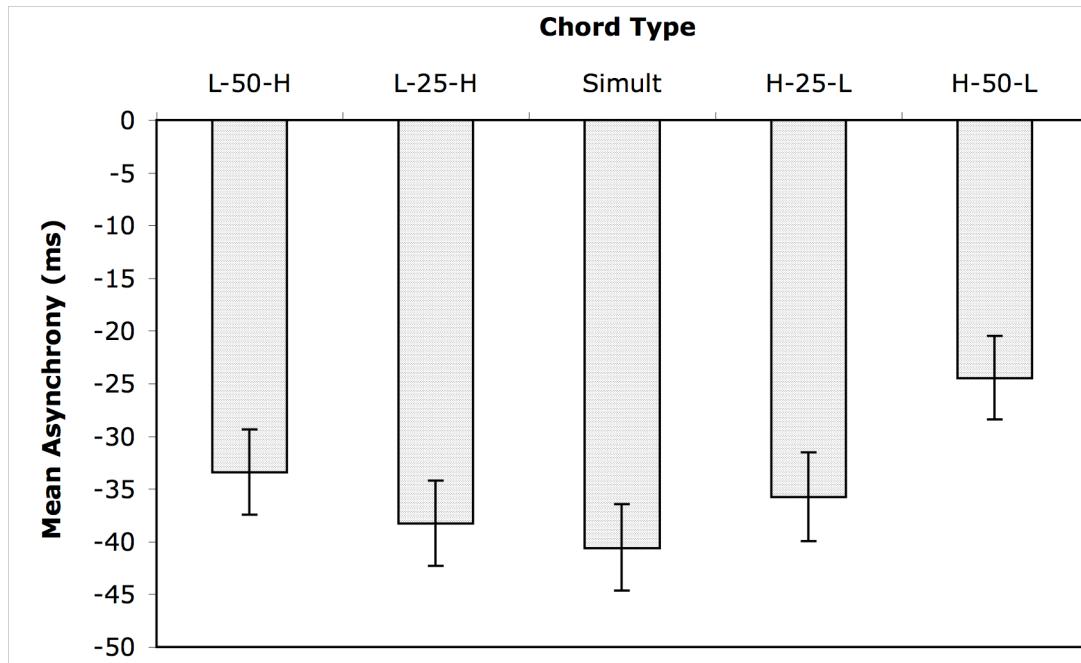
### *Procedure.*

The procedure was identical to that in Experiment 1, with the following exceptions: Each trial consisted of a single chord presented 21 times successively, with an IOI of 550 ms. Participants were instructed to start tapping with the fifth chord in each trial. Taps 5–16 (corresponding to chords 9–20) were analyzed. There were 8 blocks of 20 trials (plus one training block). Four trials from each of the 5 conditions appeared in each block, with presentation order randomized. Participants each took approximately 1 hour to complete the experiment.

### *Results and Discussion*

Data were again screened for outliers. Of the 2,720 total trials, 62 had standard deviations of tap-to-chord asynchronies greater than 60 ms (~2.5 times overall average *SD*) and were excluded. Additionally, individual tap-to-tone asynchronies were examined for anomalies. Participants occasionally stopped tapping a few beats early and would subsequently try to resynchronize, resulting in deviant asynchronies in 57 trials. These individual asynchronies were not included in the analyses reported below (165 total deleted data points from the 57 trials). Mean asynchronies in each of the five chord type conditions are shown in Figure 2 (averaged across musical experience). These data were entered into a 5 x 2 ANOVA with the within-participants factor chord type (L-50-H, L-25-H, simultaneous, H-25-L, H-50-L) and the between participants factor musical experience (musician vs. nonmusician). This ANOVA revealed a statistically significant effect of chord type on mean asynchrony [ $F(4,60) = 23.67, p < .001$ ] (the Greenhouse–Geisser correction was applied here and in all cases below when the degrees of freedom numerator exceeded 1). Neither the main effect of musical experience nor the interaction between chord type and musical experience was statistically significant ( $ps > .3$ ).





*Figure 2.2.* Average tap-to-chord asynchronies in Experiment 2 for the five different chord types (e.g., “Simult” chords have simultaneous onsets of high and low tones and in “H-50-L” chords, the high tone onset precedes the low tone onset by 50 ms). The error bars represent standard error.

The effect of chord type on mean asynchrony was unpacked using four planned orthogonal contrasts (with data collapsed across musical experience). The first contrast compared asynchronies in the chord type condition with simultaneous tone onsets (simultaneous condition) with asynchronies in the remaining conditions combined (i.e., averaged across the H-50-L, H-25-L, L-25-H, and L-50-H conditions). This contrast revealed that taps in the simultaneous condition occurred significantly earlier than taps to chords containing tone-onset asynchronies [ $F(1,16) = 33.4, p < .001$ ]. This result was expected and replicates the main result of Experiment 1. The second contrast examined the magnitude of tone-onset asynchrony (50 ms vs. 25 ms). Participants tapped significantly later for chords containing the larger tone-onset

asynchronies [ $F(1,16) = 28.4, p < .001$ ]. Thus, the amount of delay before the second tone onset affected tap timing. The third contrast examined the effect of the leading pitch (high-tone lead vs. low-tone lead). Participants tapped significantly later for chords where the high tone led [ $F(1,16) = 13.5, p < .01$ ]. It appears that low tones tend to attract taps more than high tones. The fourth contrast examined the interaction effect of high-/low-tone lead x 25/50-ms onset delay and found a significant difference [ $F(1,16) = 17.09, p < .001$ ]. This interaction can be seen in Figure 2 as a greater difference between the effect of tone-onset delay when the high tone led.

A 5 x 2 ANOVA on mean ITIs revealed that participants were, on the whole, able to tap at the correct tempo: Mean ITI was 549.73 ms (the target ITI was 550 ms) and was not affected reliably by chord type, musical training, or by their interaction ( $ps > .4$ ).

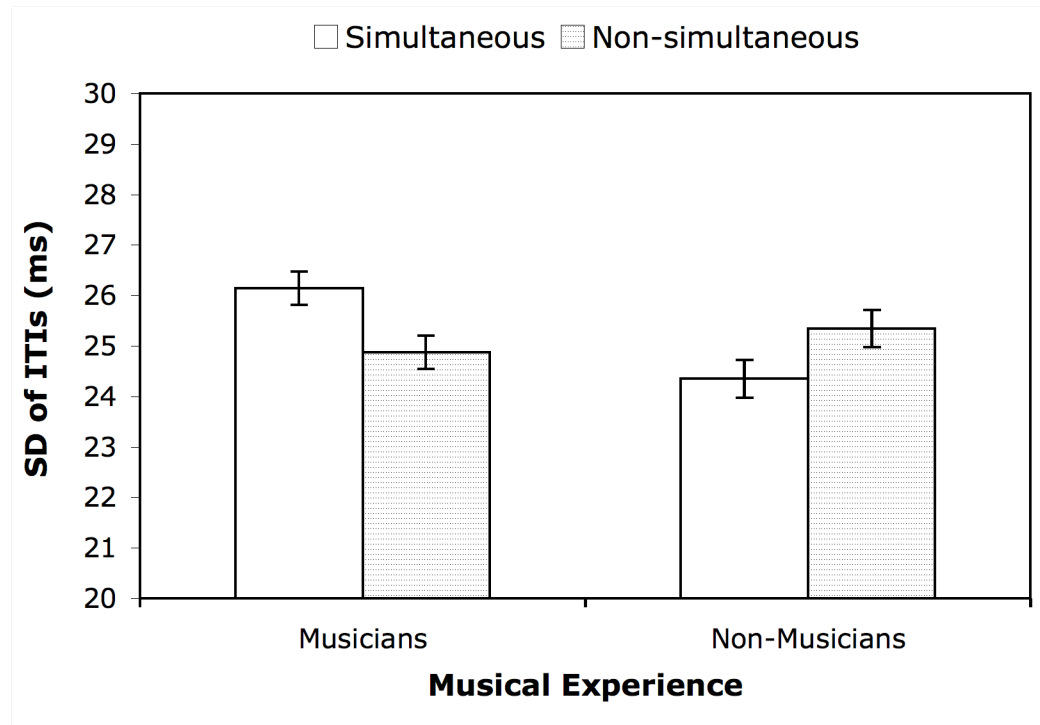
We turn now to our indices of tap timing variability. Averaged data for *SD* of asynchronies and *SD* of ITIs are shown in Table 2. A 5 x 2 ANOVA on *SD* of asynchronies revealed no significant main effects of chord type or musical experience, and no significant interaction effect for these factors ( $ps > .1$ ). However, the corresponding ANOVA on *SD* of ITIs revealed a significant effect of chord type [ $F(4,60) = 3.02, p < .05$ ]. The main effect of musical experience was not significant ( $p > .9$ ), and the interaction between chord type and musical experience approached significance [ $F(4,60) = 2.22, p = .09$ ]. A follow-up analysis employing the same four planned orthogonal contrasts described above (with musical experience included as a between-participants factor) revealed that the effect of chord type was confined to the contrast that tested effects of leading tone pitch: *SD* of ITIs was lower on average when the low tone led than when the high tone led [ $F(1,15) = 5.59, p < .05$ ]. Chords in which the onset of the low tone preceded the onset of the high tone apparently facilitated tapping regularity.

Table 2.2: *Within-Trial SD of Asynchronies and Within-Trial SD of Inter-Tap Intervals (ITIs) Averaged Across Musicians and Non-musicians from Experiment 2.*

Measure	Chord Type				
	L-50-H	L-25-H	Simult	H-25-L	H-50-L
SD of	20.52	20.97	21.07	21.05	21.46
asynchronies	(5.58)	(5.22)	(5.42)	(5.19)	(4.93)
SD of ITIs	24.38	24.90	25.08	25.35	25.97
	(6.06)	(5.75)	(5.89)	(6.22)	(5.95)

*Note.* The between-participant SD of scores on each measure is shown in parentheses. All values are in ms.

Our contrast analysis also revealed a significant interaction between chord type and musical experience on the contrast that compared *SD* of ITIs for chords with simultaneous versus nonsimultaneous onsets [ $F(1,15) = 16.42, p < .001$ ]. This effect gives weight to the results of Experiment 1. As can be seen in Figure 2.3, musicians' tapping was more stable in the nonsimultaneous conditions, on average, than in the simultaneous condition [ $t(6) = 3.55, p = .01$ ]. Nonmusicians, conversely, tapped more stably in the simultaneous condition [ $t(9) = 22.53, p < .05$ ]. Musical training did not produce a significant interaction with chord type on the remaining three contrasts [ $F_s(1,15) < 1$ ].



*Figure 2.3.* Average within-trial SD of inter-tap-intervals (ITIs) with simultaneous and non-simultaneous onset chords for musicians and non-musicians in Experiment 2. Error bars represent 95% confidence intervals calculated separately for musicians and non-musicians.

### Experiment 3

The mean asynchrony results of Experiments 1 and 2 raise the question why people tap later with chords containing onset asynchronies. Here we investigated the potential role of perceptual centers in this effect. P-centers—the subjective moments of occurrence of an acoustic signal—have been studied widely in both speech and musical contexts (e.g., Gordon, 1987; Morton, Marcus, & Frankish, 1976; Scott, 1998; J. Vos & Rasch, 1981). P. G. Vos et al. (1995) manipulated the duration and rise time of single-tone stimuli in a series of tapping experiments and demonstrated that, as predicted by the P-center hypothesis, asynchronies became less negative, with longer

stimulus durations and less steep rise times. One potential explanation for the results of Experiment 1 and 2 is that participants attempted to align their taps with the P-center of the chord, and that a chord's P-center was later when one of its constituent tones had a delayed onset. Moreover, to account for the results of Experiment 2, the P-center would need to be later when the low-tone onset followed the high-tone onset rather than the reverse. Experiment 3 was designed to test this hypothesis by measuring the P-center of the five chord types from Experiment 2. The P-center-focused explanation of the effects of onset asynchrony on synchronization would be supported by finding that the relative positioning of P-centers across the five chord types is similar to the tap positioning reflected in the mean asynchrony results from Experiment 2.

### *Method*

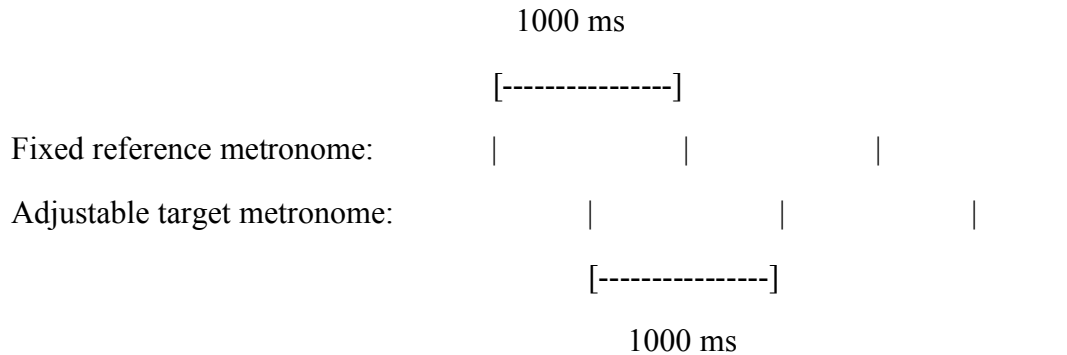
#### *Participants.*

Twelve Cornell University undergraduates participated (3 women and 9 men; age range 18–23 years, mean age, 20.2). All participants had some musical training, ranging from 3 to 12 years of instruction ( $M = 7.0$ ). Six “musicians” had more than 6 years of formal training. Participants received course credit for their participation, and were previously unfamiliar with the task.

#### *Materials and Procedure.*

The same five chords as in Experiment 2 were used. Participants sat in front of a Macintosh laptop and listened to the tones over AKG K141 headphones. Tones were presented and data were recorded using a program written in MAX. Participants initiated each trial with a mouse click, which in turn triggered two interleaved metronomes, both with IOIs of 1,000 ms, as shown in Figure 2.4. The constant “reference” metronome started; then, after a delay, so did the adjustable “target” metronome. The initial delay of the target metronome was

randomly selected from a range of 300–700 ms with a step size of 1 ms.



*Figure 2.4.* Graphical depiction of the interleaved metronomes in Experiment 3.

Between 300 and 700 ms after a fixed reference metronome commenced, an adjustable ‘target’ metronome started. Participants adjusted the phase of the target metronome until they felt that the two metronomes’ respective onsets bisected each other.

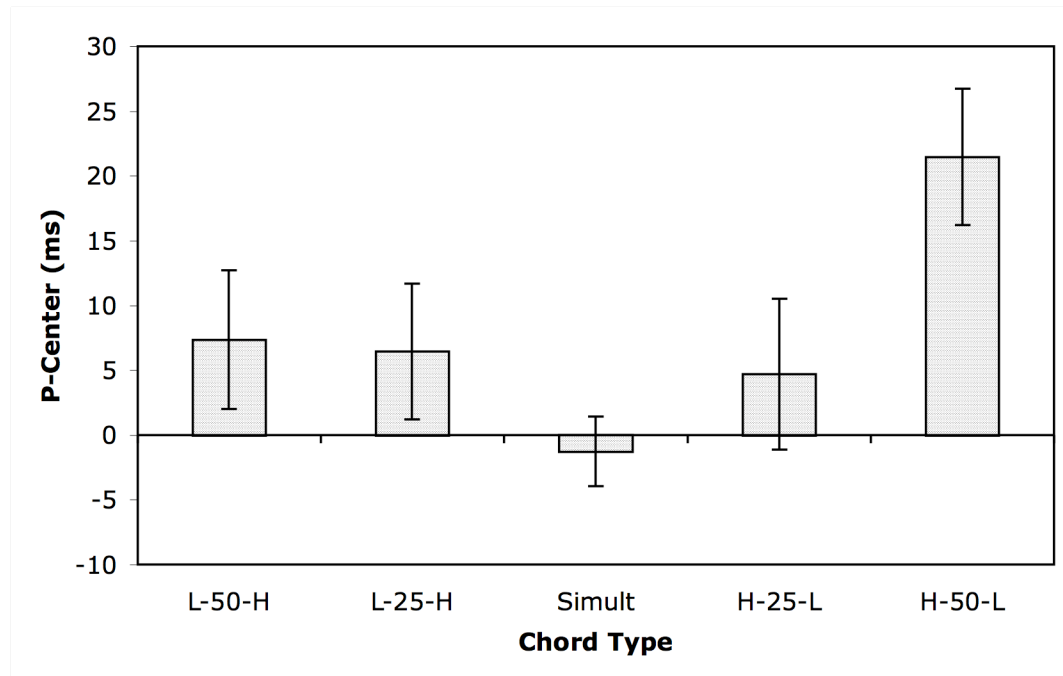
Participants were instructed to adjust the target metronome so that its onsets bisected the reference metronome onsets. The target metronome onsets could be shifted by clicking one of 4 buttons: a large left arrow, a small left arrow, a small right arrow, and a large right arrow. These keys had the effect of shifting the target metronome 15 ms earlier, 1 ms earlier, 1 ms later, and 15 ms later, respectively. When participants felt that the onsets of the two metronomes were equally spaced in time, they could click a button labeled “Just Right” and commence the next trial.

Reference metronome tones were always the simultaneous chords from Experiment 2, in which the high and low tones were presented simultaneously. The target metronome tones were one of the five chord types from Experiment 2 (H-50-L, H-25-L, simultaneous, L-25-H, L-50-H). The five trial types were presented 10 times each for a total of 50 trials in the experiment. Participants took between 45 and 70 min

to complete the experiment.<sup>9</sup>

### *Results and Discussion*

The P-center for each chord type was calculated by measuring its mean adjusted onset time after the preceding reference metronome onset and then subtracting 500 from this value. For example, the target metronome onset (i.e., the onset of the first tone) for H-50-L chords was, on average, 479 ms after the reference metronome onset, so its perceived onset occurred 21 ms after the actual onset of the first tone of the chord in the target metronome.



*Figure 2.5.* Average P-centers for the five chord types, as measured relative to the onset of the chord's first tone in Experiment 3. For example, the H-50-L chord's P-center is 21 ms after its initial tone onset. The error bars represent standard error.

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<sup>9</sup> Data from one nonmusician (male, age 20) were not analyzed, because more than half of his trials were not recorded due to a technical error.

Average P-centers for the five chord types are shown in Figure 2.5. Note the qualitative resemblance between the pattern of results in this graph and the mean asynchrony results from Experiment 2 (Figure 2). A 5 x 2 ANOVA with the within-participants factor chord type and the between-participants factor musical experience (musician vs. nonmusician) on the P-center data revealed neither an effect of musical experience nor an interaction ( $ps > .3$ ). However, the ANOVA revealed a significant effect of chord type [ $F(4,36) = 12.10, p < .001$ ]. Borrowing the logic used in Experiment 2, this effect was unpacked using four planned orthogonal contrasts (with data collapsed across musical experience). The first planned contrast revealed that the P-center was later for chords containing tone-onset asynchronies than for chords with simultaneous tone onsets [ $F(1,10) = 11.23, p < .01$ ]. Second, the P-center was, on average, later for chords with large tone-onset asynchronies than for small onset asynchronies [ $F(1,10) = 29.40, p < .001$ ]. Third, the P-center was, on average, earlier for chords in which the low tone led than when the high tone led [ $F(1,10) = 6.62, p < .05$ ]. This effect was largely due to a very late P-center for chords where the high tone led by 50 ms, as evidenced by a significant interaction between the pitch of the leading tone and the magnitude of the tone-onset asynchrony [ $F(1,10) = 8.98, p = .02$ ]. Thus, the results of the statistical analysis are qualitatively the same as those observed for mean asynchrony in Experiment 2. P-centers seem to go quite some way in explaining the earlier results; the question is, can they go all the way?

To test the degree to which P-centers accounted for the effects of chord type on mean asynchronies in Experiment 2, we entered the pooled data from Experiments 2 and 3 into a 5 x 2 ANOVA with the within-participants factor chord type and the between participants factor experiment. Not surprisingly, this ANOVA revealed a significant main effect of chord type, which simply reflects the fact that chord type affected both tap placement and P-centers [ $F(4,104) = 32.47, p < .001$ ]. A significant



main effect of experiment was also observed [ $F(1,26) = 18.69, p < .001$ ]: Taps (recorded in Experiment 2) preceded P-centers (measured in Experiment 3) by 42.8 ms on average. However, the interaction between chord type and experiment was not significant [ $F(4,104) = 1.36, p > .2$ ]. This suggests that the relative positioning of taps across the chord-type conditions can be accounted for largely by differences in P-centers between the chord types.

### General Discussion

The three experiments reported here were motivated by the observation that nonsimultaneous tone onsets occur commonly in polyphonic music such as solo piano performance (e.g., Palmer, 1996; Repp, 1996) and in ensemble performance (Prögler, 1995; Rasch, 1988). Our main question was whether such tone-onset asynchronies affected sensorimotor synchronization. The first two experiments examined how tone-onset asynchronies within the chords of a pacing sequence affected tap timing accuracy (i.e., tap placement relative to chord onsets) and variability (ability to maintain a constant phase relationship and tapping tempo). The final experiment investigated whether the observed effects could be attributed to shifts in the perceptual onsets (the P-centers) of the chords.

#### *Tap Timing Accuracy*

In the first two experiments, we obtained the common result that taps precede stimulus onsets by 25–50 ms. These negative mean asynchronies support the idea that, in sensorimotor synchronization, physical onsets of external events (taps and tone onsets) are not synchronized; rather, synchrony is established on a central level of subjective simultaneity (Aschersleben, 2002), so that the P-centers of taps and tones are aligned. Because processing delays are longer in the tactile than in the auditory modality, taps must occur “early” for perceptual co-occurrence. Negative asynchronies

were found for two-tone chords with both simultaneous and nonsimultaneous onsets in Experiments 1 and 2, but the magnitude of the asynchrony varied. Our results indicate that asynchronies between taps and initial chord onsets shifted toward the onset of a delayed second tone and that the shift was larger when the second tone onset was delayed longer. However, the magnitude of shift was much less than half the difference between the first and second tone onsets. For example, chords containing a 25-ms onset delay had average tap shifts of approximately 3 and 5 ms (depending on whether the high tone preceded the low tone or vice versa, as discussed below) rather than of 12.5 ms, and chords containing a 50-ms onset delay had average tap shifts of 7 and 15 ms rather than of 25 ms. Thus, the first tone onset of a chord has a larger influence on determining tap timing than a subsequent onset in the chord. Presumably, the first onset is more perceptually salient.<sup>10</sup>

Results from Experiment 3 showed similar shifts in a chord's P-center as a function of onset delay of one component. The magnitude of P-center shift was again smaller than the mean onset difference. For chords with a 25-ms onset asynchrony, we saw shifts in P-center of 6 and 8 ms relative to the simultaneous-condition P-center (depending on whether the high or low tone led); for chords with a 50-ms delay, we observed shifts of 9 and 22 ms. The fact that these effects are smaller than half the difference between the tone onsets supports the idea that the first tone onset is more important in determining the group's P-center. Thus, the effects of nonsimultaneous tone onsets within a chord are somewhat analogous to the effects of lengthening a

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<sup>10</sup> P. G. Vos et al. (1995) found evidence for the perceptual dominance of onsets in single tones of various durations. Taps were shifted toward the physical center of longer tones, but the physical onset was clearly a greater determinant of tap timing, since taps did not coincide with the midpoints of the tones.

sound's duration or decreasing the steepness of its rise time.

Pooled data from Experiments 2 and 3 revealed that a chord's P-center largely accounts for tap timing when that chord is used in a pacing sequence. As stated above, we assume that participants attempt to line up P-centers for taps and tones. The perceived onsets of taps (i.e., P-centers established on the basis of efferent and afferent movement-related information) are presumably relatively constant across our conditions. So when the P-center for tones changes as a function of chord type, tap timing must change in order to realign the tap P-centers with the new tone P-centers. When the tone P-centers occur later than the P-centers of chords with simultaneous tone onsets, taps must be delayed so that their P-centers are aligned with the tone P-centers.

Our findings are consistent with previous work that has shown that when multiple tones sound within a perceptual temporal integration window of approximately 100–150 ms, the tones are perceived as a tightly bound group rather than as separate events (Repp, 2005; Yabe et al., 1998). In a related study mentioned briefly in the introduction, Repp (2003, Experiment 2) asked participants to synchronize tapping with a target sequence and to ignore a distractor sequence of a different pitch in which tones slightly preceded or followed tones in the target sequence. Participants' tap timing inadvertently shifted more toward early distractors than late distractors. For example, when distractors preceded targets by 40 ms, taps shifted approximately 30 ms earlier, whereas when distractors followed targets by 40 ms, taps shifted approximately 8 ms later. These results align nicely with our findings, namely that multiple onsets occurring close together are perceived as an integrated unit and subsequent tap timing is dictated by a weighted average of component onsets with more “weight” placed on the first onset.

We observed pitch differences indicating that low tones had a greater effect on

tapping. The anticipation tendency is smaller for chords with delayed low tones, because the P-center is later for these chords. Additionally, the ability to maintain a steady tapping tempo was best for chords in which the onset of the low tone preceded the onset of the high tone. In the Repp (2003) study mentioned above, a few weak effects of pitch on tap timing were observed; participants could synchronize with low-pitch targets and ignore high-pitch distractors better than vice versa. These results are consistent with our finding that lower pitched tones attract taps more than higher pitched tones when both high and low pitched tones are present. In a related experiment, Handel and Lawson (1983) presented participants with polyrhythms (e.g., 2:3, 3:4, 4:5, and 3:4:5) consisting of different pitched pulse trains, and examined rhythmic interpretations via participants' preferred tapping patterns. Participants tended to select the lowest pitched pulse train as the polyrhythm meter. A possibility to consider is that low tones mask delayed high tones more than vice versa because of the "upward spread of masking" (Moore, 1997). A decrease in onset salience of high tones that follow low tones might result in the high tones' relatively small impact on P-center judgments. It should be noted, however, that in the present experiments the high tones were easily audible so only partial masking may have occurred, if any.

Finally, the results may be related to the musical convention that often assigns the role of setting the beat to low-pitched instruments (e.g., walking bass lines in jazz, tuba in oompah bands, the left hand in ragtime piano, "four on the floor" bass drum in some electronic music). Our participants may have been influenced by this musical convention, or the convention itself may be rooted in the greater perceptual salience of lower tones. Additionally, there may be a contribution of a cross-modal system that favors a connection between low tones and physical movements. Indeed, the low, loud sounds encountered in techno dance music have been shown to evoke a vestibular response that may be pleasurable and may induce movement (Todd, 2001; Todd &

Cody, 2000).

### *Tap Timing Variability*

Our two synchronization experiments also revealed some effects of the type of chord onset (simultaneous or nonsimultaneous) on the variability of tap timing. These effects were subtle (it should be noted that data from trials with abnormally high variability were excluded from our analyses). The most revealing measure of tapping variability was the *SD* of the ITIs, which is an index of how well participants were able to tap at a steady tempo. The effect of chord onset asynchronies on this measure depended on musical experience. Chords with nonsimultaneous onsets tended to decrease tap regularity for participants with little or no musical training. This is what would generally be expected if the nonsimultaneous onsets introduced uncertainties in either perception or how the task was to be performed. In contrast, nonsimultaneous onsets actually facilitated tap regularity for participants with considerable musical training. We will briefly explore a few factors potentially contributing to this effect. Note that the mechanisms invoked by these explanations may operate independently of those that determine P-centers.

Facilitation of tapping regularity would result from increased constancy of motor command pulses established by auditory input. Although slightly counterintuitive, multiple proximal onsets might actually increase the precision of temporal pulse in later stages of processing. Each temporal event has an associated variance, and, assuming additivity of variance, the *SD* of the weighted average of multiple onsets will be less than that of single onsets. If musicians could efficiently integrate nonsimultaneous onsets this variance would decrease.

Alternatively, increased tapping regularity might result if nonsimultaneous onsets rendered error correction mechanisms less active. Numerous synchronization models (e.g., Mates, 1994a, 1994b; Pressing, 1998; Semjen, Schulze, & Vorberg,

2000; Vorberg & Wing, 1996) propose that taps are adjusted by a proportion of recent synchronization error in order to mitigate drift; however, the adjustments have an associated “cost” of increased ITI variability (Semjen et al., 2000; Voillaume, 1971). A number of researchers (e.g., Mates, 1994a; Schulze & Vorberg, 2002) suggest that the asynchrony must exceed a certain threshold before error correction mechanisms are engaged, although most existing error correction models do not include such a threshold, an exception being Mates’s (1994a, 1994b) model.<sup>11</sup> In the present context, nonsimultaneous onsets may have enlarged the span of time over which deviations are too small to engage error correction mechanisms. In other words, when there are two onsets, the likelihood of “being on the beat” increases, so phase correction responses would be less active and ITI variance would decline.

A final explanation of why onset asynchrony might reduce tapping variability for some participants has to do with dynamical systems models, self-sustained internal oscillators, and entrainment (Large & Jones, 1999; Large & Palmer, 2002). According to Large and Jones’s (1999) model of perception and attention, an adjustable oscillating “attentional pulse” reacts only to onsets that occur close to the time at which they are expected to occur; if the metronome onset does not occur at the peak of the internal oscillator’s temporal cycle but is still within the range of the attentional pulse, a readjustment of the internal oscillator’s phase is caused. If the oscillator and external beats frequently coincide, the region of sensitivity will shrink; conversely, if internal and external oscillations are more variable, the region will widen. Of greatest relevance to the present results, Large and Palmer (2002) showed that the model was

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<sup>11</sup> Schulze and Vorberg (2002) demonstrated the difficulty of trying to detect a threshold empirically and showed that linear correction parameters can provide an excellent approximation “before more realistic but complex models arrive.”

better at tracking temporal changes in a pulse when the pulse was articulated by chords with multiple onsets. In other words, two onsets will increase the likelihood of “being on the beat.” Although these models are of perception–attention coupling, “being more on the beat” might improve perception–action coupling as previously mentioned. Another possibility is that, although the peaks are wider, they are more regularly spaced, which could facilitate tapping stability. Finally, nonsimultaneous onset chords might represent a stronger dynamical attractor, because there is more perceptual information to lock onto. Whereas existing models of synchronization may not directly address our manipulations of asynchrony or the importance of pitch, extensions thereof could.

### *Conclusions*

The main outcome of the current study is that sensorimotor synchronization is affected markedly by tone-onset asynchronies that fall within the range of asynchronies observed in multipart music performance. Our results suggest that such onset asynchronies affect the P-centers of chords in the pacing sequence thereby influencing the location of the temporal target for synchronization. This effect of onset asynchronies on tap placement appears to be independent of musical experience, implying that its source lies in a natural synergy between perception and action during synchronization.

On the other hand, more subtle effects of onset asynchronies on the ability to maintain a steady tapping tempo appear to be modulated by musical experience. Individuals with large amounts of musical performance experience, in contrast to individuals with little or no such experience, displayed greater tempo stability when onset asynchronies were present than when such asynchronies were absent. Although this finding may seem surprising at first, it can be accounted for by a combination of various existing theoretical assumptions; furthermore, it falls well within the realm of

musical intuition. Musical experts should deal better than novices with structural ambiguity in a pacing sequence. Years of exposure to nonsimultaneous tone onsets might lead to the avoidance of any potential conflict by allowing musicians to perceive an integrated “beat” under such circumstances, whereas nonmusicians might be confused by onset asynchronies, potentially leading to the perception of multiple displaced beats.

However, far from merely dealing relatively well with structural ambiguity, musicians may in fact thrive on it. Musicians debate whether it is better to play in strict simultaneity or slightly out of phase (Keil, 1995). The present work might offer this insight: The beat you play depends on the audience. When playing for other musicians, nonsimultaneity or a “wide beat” will result in more regular movements (dance steps, head bobs, finger snaps), and will, therefore, arguably be more enjoyable. On the other hand, nonmusicians move more regularly with “unambiguous” synchronous onsets, hence, such simultaneity may be preferred. This difference in beat preference is reflected in the music industry. Much popular music today is quantized, and this absence of microtiming deviations may appeal to many of the musically untrained consumers. Conversely, musical training might increase appreciation of expressive microtiming deviations and onset asynchronies that are common in live groove-based music.



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## CHAPTER 3

### COMPATIBILITY OF MOTION FACILITATES VISUOMOTOR SYNCHRONIZATION<sup>12</sup>

#### Abstract

Prior research indicates that synchronized tapping performance is very poor with flashing visual stimuli compared with auditory stimuli. This observed difference may reflect a general auditory advantage for processing temporal information, while visual processing may have an advantage with spatial information. Three finger-tapping experiments compared flashing visual metronomes with visual metronomes containing a spatial component, either compatible, incompatible, or orthogonal to the tapping action. In Experiment 1, synchronization success rates increased dramatically for spatiotemporal sequences of both geometric and biological forms over flashing sequences. In Experiment 2, synchronization performance was best when target sequences and movements were directionally compatible (i.e. simultaneously down), followed by orthogonal, action-neutral stimuli, and was poorest for incompatible moving stimuli (upward target/downward movement) and flashing target sequences. In Experiment 3, synchronization performance was best with auditory sequences, followed by compatible moving stimuli and was worst for flashing and fading sequences. Results indicate that visuomotor synchronization improves dramatically with compatible spatial information (translation over time). However, an auditory advantage in sensorimotor synchronization persists.

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<sup>12</sup> Hove, M. J., Spivey, M. J., & Krumhansl, C. L. (submitted). Compatible motion facilitates visuomotor synchronization.

## Introduction

Sensorimotor synchronization is generally found to be more difficult and more variable with visual rhythms than auditory or tactile rhythms. People rarely synchronize spontaneously with purely visual rhythms, whereas they do with music. The ability to synchronize with music is observed in young children (Eerola, Luck, & Toiviainen, 2006), with a wide range of musical styles (van Noorden & Moelants, 1999), and after hearing only a few beats (Snyder & Krumhansl, 2001). Rhythmic finger tapping has been found to be most variable with flashing visual stimuli and least variable with auditory stimuli (Chen, Repp, & Patel, 2002; Repp & Penel, 2002, 2004), with tactile stimuli intermediate (Kolers & Brewster, 1985). Moreover, reliable synchronization in 1:1 tapping is possible at rates as fast as an inter-onset interval (IOI) of about 200 ms for auditory sequences (e.g., Fraisse, 1982),<sup>13</sup> contrasted with IOIs around 460 ms for flashing visual sequences (Repp, 2003).

The apparent difficulty in synchronizing with visual stimuli has yet to be explained adequately. It may simply stem from the less frequent occurrence of visual than auditory rhythms in our environment. Another possibility is that it is based on differences in neural connectivity. Fraisse (1948) suggested that the action system is more closely linked to the auditory system than to the visual system. More recently, Thaut and colleagues (1999) proposed a comparatively direct connection between auditory cortex and spinothalamic neurons used to control movement, which results in increased sensorimotor coupling. Yet another possibility for the observed performance

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<sup>13</sup> The rate limit in 1:1 tapping seems to reflect the maximum finger frequency. When tapping with every 4<sup>th</sup> onset, the auditory IOI limit decreases to 100-120 ms (Repp, 2003).

differences stems not from differential connectivity between motor neurons and auditory versus visual pathways, but from the inherent processing styles of those two sensory systems themselves. The auditory system is generally better at resolving temporal variation (e.g., Conway & Christiansen, 2005), whereas the visual system is better at resolving spatial variation (e.g., Posner, Nissen, & Klein, 1976). Under this account, visual information naturally dominates when one is attempting to identify the *spatial location* of a sound (as in the ventriloquism effect; Bertelson & Radeau, 1981), and auditory information naturally dominates when one is attempting to identify or behave contingent upon the *temporal incidence* of a sound (as in synchronized tapping tasks, Repp & Penel, 2002, 2004).

The observed difficulties in visuomotor synchronization may appear simply because the vast majority of studies employ purely temporal flashing stimuli devoid of spatial information. This focus on flashing stimuli dates back a century (Dunlap, 1910), and more recently extends into examinations of the neural substrates of visuomotor synchronization in fMRI (e.g., Jäncke, Loose, Lutz, Specht, & Shah, 2000), PET (Penhune, Zatorre, & Evans, 1998) and MEG (Chen, Ding, & Kelso, 2003). Repp, Patel and colleagues (Patel, Iverson, Chen, & Repp, 2005; Repp & Penel, 2004) have speculated that different types of visual stimuli, namely those employing a spatial component, might facilitate synchronization.

A great deal of literature explores stimulus-response compatibility effects but compatibility effects have not yet been demonstrated in the synchronized tapping paradigm. Studies of the synchronization of hand movements with an oscillating visual target found that in-phase movements were more stable than anti-phase movements (Roerdink, Peper, & Beek, 2005; Wimmers, Beek, & van Wieringen, 1992; for perception-action compatibility effects in bimanual coordination, see e.g., Bogaerts, Buekers, Zaal, & Swinnen, 2003; Mechsner, Kerzel, Knoblich, & Prinz,



2001). However, it remains unclear how such results would compare with purely temporal flashes or action-neutral moving stimuli. Additionally, facilitative effects of compatibility between dynamic visual displays and finger movements have been observed in reaction time tasks (Brass, Bekkering, & Prinz, 2001), and may extend to synchronization performance. Finally, the extrastriate body area (EBA) in human occipital cortex responds selectively to images of the human body (Downing, Jiang, Shuman, & Kanwisher, 2001) and also is active during limb movements (Astafiev, Stanley, Shulman, & Corbetta, 2004). This suggests a link between perceptual and action-based body representations, and might translate into different synchronization performance with human body images versus geometric images. In the following experiments, we investigate whether certain types of spatially varying and compatible visual information enable better synchronization than simple flashing or fading lights.

## Experiment 1

Experiment 1 investigated sensorimotor synchronization with visual metronomes that were either purely temporal or contained additional spatial information. Those containing spatial information showed motion of either geometric or biological forms, which might afford different performance. Sequences were presented at 2 tempi: 500 ms inter-onset-interval (IOI) and 400 ms IOI; one above and one below the previously ascertained rate limit for flashing visual stimuli (Repp, 2003). The primary measures of performance were the success rate of synchronizing with the stimuli (i.e. the percent of trials that had consistent tap-to-target asynchronies as determined by Rayleigh tests for uniform distribution) and the mean phase or direction of taps relative to the targets (tap timing).

### *Methods*

#### *Participants.*

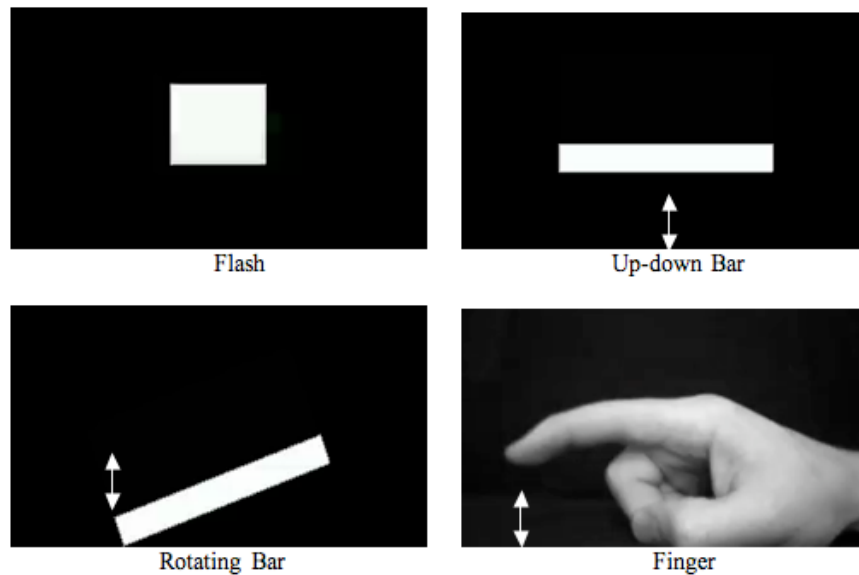
Eleven right-handed Cornell students (6 women) aged 19 to 23 years participated in the study. They were previously unfamiliar with the tapping task. Musical training ranged from 0-12 years ( $M = 4.1$ ), though most were no longer active musicians; musical training yielded no significant effects. Participants received course credit or were paid \$6.

### *Materials.*

The four stimulus sequences were QuickTime movies produced using the animation software, After Effects. They were presented on a computer screen in a 10 cm x 8 cm viewing window. Videos lasted 26 cycles and each cycle consisted of 20 frames. In the *Slow* tempo condition (500 ms IOI), videos were played at a frame rate of 40 frames per second (fps), and in the *Fast* tempo (400 ms IOI), the same videos were played at 50 fps.<sup>14</sup> The four visual metronomes are shown as still pictures in Figure 3.1.

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<sup>14</sup> The monitor refresh rate of 85 Hz (11.7 ms) led to slight deviations of frame timing. However, no systematic error or drift occurred. Timing perturbations on this order were recently shown to have no effect on variability of inter-tap-interval or tap-to-target asynchrony (Madison & Merker, 2004).



*Figure 3.1.* Stills from the four metronomes in Experiment 1; arrows added to depict motion.

The *Flash* was a 2 cm x 2 cm stationary white square that remained on screen for 2 video frames. The *Up-down Bar* was a 5 cm x 1 cm white bar that moved down frame-by-frame from its initial position 2.5 cm above the bottom of the viewing window to the bottom of the viewing window and back again. The *Rotating Bar* utilized the same bar and initial position as the *Up-down Bar*, but the bar pivoted from its right edge until the left edge touched the bottom of the viewing window, then returned to its initial horizontal position. The *Finger* used spliced images of a right index finger (5 cm x 1 cm) tapping in the same configuration as the participant's finger; the *Finger's* vertical trajectory matched the *Rotating* and *Up-down bars* frame-by-frame, thereby isolating the effect of the image of bodily form, without confounding the acceleration and deceleration of biological motion. The target position (for signaling the time to tap) in all the spatial metronomes was contact with

the bottom of the screen; this was displayed for 2 frames to match the *Flash* target duration.

#### *Procedure.*

Participants sat approximately 75 cm in front of a computer monitor that displayed the visual sequences at eye level. They positioned their right hand in front of themselves at approximately waist level perpendicular to the screen (pointing to the left) and tapped with their right index finger on a Roland Handsonic HPD-15 drum pad. Sequences were presented and taps were recorded using a MAX/Jitter program running on a Macintosh G4.

Participants were instructed to start tapping with the 5<sup>th</sup> cycle in the 26-cycle sequence; thus each trial consisted of 22 taps. Each of the eight trial types (2 tempi x 4 metronome types) was presented in random order in a block. The experiment consisted of twenty blocks, including one training block, thus leaving 152 analyzed trials per participant. The entire experiment lasted approximately 45 minutes.

#### *Analyses*

Synchronized tapping experiments are typically analyzed using linear time series methods, wherein taps and targets are aligned on a linear time scale and their respective asynchronies are calculated. However, linear methods can be problematic with variable periodic data sets. For example, if a tap occurs nearly equidistant between two targets, one must decide which target to use for the asynchrony calculation, and a single large asynchrony with linear methods can greatly skew measures of variability. These issues can be circumvented using circular statistical methods (e.g., Fisher, 1993), wherein each tap in a trial is mapped onto a unit circle in terms of its relative phase (0-360°) from the periodic metronome target (always at 0°). Synchronization performance can then be assessed in terms average phase (*when* taps tend to occur relative to the target) and the variability of the taps' relative phases (the

stability or degree of tap-to-target synchrony). Visuomotor synchronization, especially at fast tempi, can generate unwieldy data. Thus, circular statistical methods provide a cleaner and more appropriate assessment of synchronization performance for this work (see e.g., Fisher, 1993; Large & Palmer, 2002; or Kirschner & Tomasello, 2009, for more in depth discussion of circular analyses)<sup>15</sup>.

Tap timing was calculated in terms of each tap's relative phase (0-360°) from the target; e.g., taps slightly after the target have a mean phase of 0-90° and slightly before the target = 270-360°. Synchronization typically requires a few taps to stabilize, so taps corresponding to the first 7 video cycles (the first 3 taps) were omitted. An indicative measure of synchronization performance is the percentage of trials in which tap-to-target phases never stabilize (Repp, 2003). Each trial's tap-to-target synchronization performance was assessed using a Rayleigh test of uniformity, which tests the null hypothesis of a non-uniform distribution of tap-to-target relative phases against the alternative hypothesis of a unimodal distribution of tap-to-target relative phases. For each trial, the null hypothesis of non-uniformity was rejected if the Rayleigh test p-value was less than .05; these trials had a uniform distribution of tap-to-target relative phases and were defined as successful, as opposed to trials with a non-uniform distribution of taps that would occur with irregular tapping or phase drift. Success rates can then be analyzed for the different metronomes and tempi.

Comparing the mean relative phases, or any circular response in multifactor designs, however, is problematic as “very little statistical methodology is available for

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<sup>15</sup> Analyses were also run using linear methods, wherein trial success used a threshold criterion based on the SD of tap-to-target asynchronies less than 16.7% of IOI, following Repp, 2003. The success rates were very similar and results did not qualitatively differ from circular methods.

analyzing data from experiments in which a circular response has been measured at various levels of two or more explanatory variables” (Fisher, 1993, p. 133).

Multifactor ANOVAs for circular data do not exist, making it impossible to have factors benefit from the relative apportioning of unique and shared variance.

Therefore, relative phase data were analyzed separately in one-way circular ANOVAs for tempo and for type of metronome.

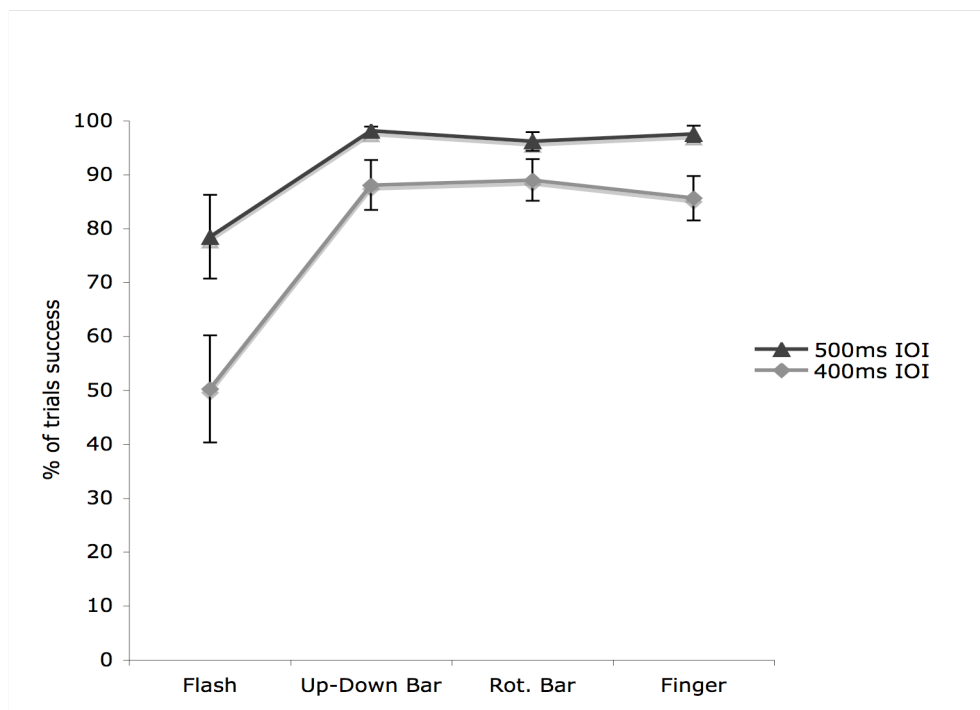


Figure 3.2: Percentage of successful trials in Experiment 1, as determined by a Rayleigh test of uniformity.

### Results and Discussion

The average percentage of successful trials by condition is shown in Figure 3.2. A 2 (tempo) x 4 (metronome type) repeated measures analysis of variance (ANOVA) revealed a main effect of metronome type, where successful trials were more frequent for the spatial metronomes than the Flash metronome,  $F(3,30) = 21.0, p < .001, \eta_p^2 =$

.67. No significant differences among the spatial metronomes were found in pair-wise comparisons,  $ps > .8$ . Additionally, there was a main effect of tempo; more successful trials occurred at the Slow tempo than at the Fast tempo,  $F(1, 10) = 18.7, p < .01, \eta_p^2 = .65$ . The Metronome x Tempo interaction was significant,  $F(3, 30) = 17.8, p < .01, \eta_p^2 = .32$ , indicating that the fast tempo was more debilitating for the Flash than for the spatial metronomes.

Participants could not consistently tap with the Flash metronome in the fast (400 ms IOI) tempo condition and were not better than a 50% “synchronization threshold,” consistent with Repp (2003). However, success rates for the three spatial metronomes were well above the 50% synchronization threshold even in the Fast tempo condition. This indicates that visuomotor synchronization rate limits for spatially varying metronomes are lower than the previously measured rate limits for flashing metronomes.

Analyses of tap timing showed that taps tended to precede targets, as is commonly found (e.g., Aschersleben, 2002), although mean relative phase or asynchrony is generally not treated as an index of synchronization success. An ANOVA revealed a main effect of tempo: participants anticipated the target to a greater extent at the slow tempo,  $F(1,86) = 12.9, p < .001$ . On average, participants tapped 45 ms before the target at the slow (500 ms) tempo (mean direction =  $327.1^\circ$ ), and 2 ms before the target at the fast 400 ms IOI tempo (mean direction =  $358.1^\circ$ ). This decrease in anticipation tendency is common at faster tempi (e.g., Repp, 2003), but the reason for this remains unclear (see Repp, 2005, for a recent review of competing explanations). Metronome type yielded no effect overall,  $F(3,84) = .56, p > .6$ ; nor was there an effect of metronome type on mean relative phase at just the slowest, most-stable tempo,  $p = .8$ .

In summary, the addition of a spatial component facilitated visuomotor synchronization success and participants easily synchronized with these metronomes even at the fast 400 ms IOI tempo. No advantage for tapping with biological forms over geometric forms was observed. The anticipation tendency was greater at the slow tempo.

## Experiment 2

Experiment 2 investigated whether the moving visual metronomes' degree of compatibility with the to-be-performed movement influenced synchronization performance. Participants synchronized finger tapping with 4 types of visual metronome. Sequences were presented at three tempi: the two from Experiment 1, plus a faster tempo in order to examine whether synchronization might be possible at even higher rates.

### *Method*

#### *Participants.*

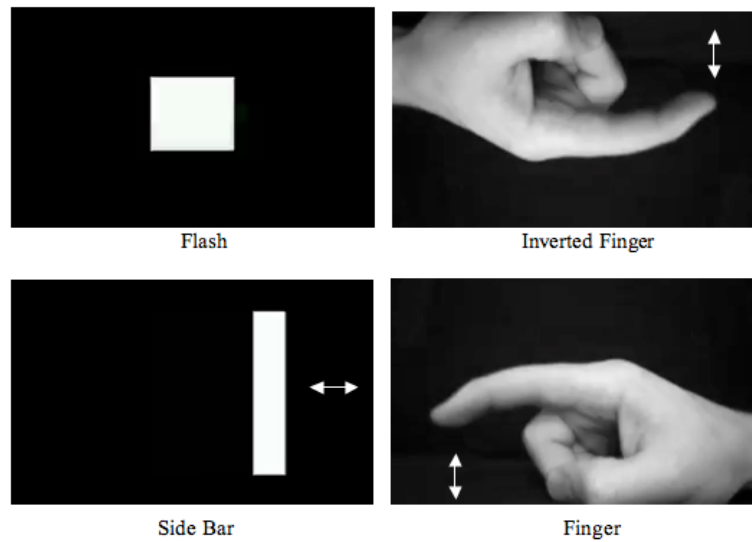
Thirteen right-handed Cornell students (8 women) aged 19 to 21 years participated in the study. They were previously unfamiliar with the tapping task. Musical training ranged from 0-10 years ( $M = 4.6$ ), though most were no longer active musicians; musical training yielded no significant effects. Participants received course credit or \$6.

#### *Materials.*

The QuickTime videos were played at 3 IOIs: 500 ms (*Slow*); 400 ms (*Fast*); and 300 ms (*Very Fast*). The four metronome types are shown in Figure 3.3. The *Flash* and *Finger* videos from Experiment 1 were used. In the *Finger* video, stimuli and tapping movement were directionally compatible. The *Inverted Finger* was the *Finger* video flipped upside down and the target for tapping occurred when the finger



contacted the top of the window; stimuli and tapping movement were incompatible. The left-and-right moving bar (*Side Bar*) was the Up-down Bar from Experiment 1 rotated 90 degrees counter-clockwise, so the target occurred when the bar struck the viewer window's right edge; stimuli were orthogonal and action-neutral with respect to the tapping movement. The three spatial videos had identical trajectories and tested the degree of compatibility between stimuli and movement.



*Figure 3.3:* Stills from the four metronomes in Experiment 2; arrows added to depict motion.

#### *Procedure.*

The procedure was identical to Experiment 1, except that there were 15 blocks containing each of the 12 trial types (3 tempi x 4 metronome types) in random order. The first block was considered training, thus leaving 168 analyzed trials. The experiment lasted approximately 50 minutes.

#### *Results and Discussion*

The data were preprocessed as before. The percentage of successful trials by condition is shown in Figure 3.4. A 3 (tempo) x 4 (metronome type) ANOVA found a main effect of metronome type,  $F(3, 36) = 14.9, p < .001, \eta_p^2 = .55$ . Pair-wise comparisons showed synchronization performance was better for the compatibly moving Finger than all other metronomes ( $ps < .01$ ). The neutrally moving Side Bar yielded better performance than the incompatible Inverted Finger and non-spatial Flash ( $ps \leq .05$ ). There was no difference between the Flash and the Inverted Finger ( $p > .95$ ). The main effect of tempo was also significant,  $F(2, 24) = 50.3, p < .001, \eta_p^2 = .80$ . Pair-wise comparisons showed the most failed trials at the Very Fast (300 ms IOI) tempo ( $ps < .001$ ); and more failed trials at Fast (400 ms IOI) than Slow (500 ms IOI) ( $p < .001$ ). The Metronome x Tempo interaction was not significant,  $p > .4$ . Success rates for the compatible Finger metronome are over a 50% “synchronization threshold” even at the fastest 300 ms IOI.

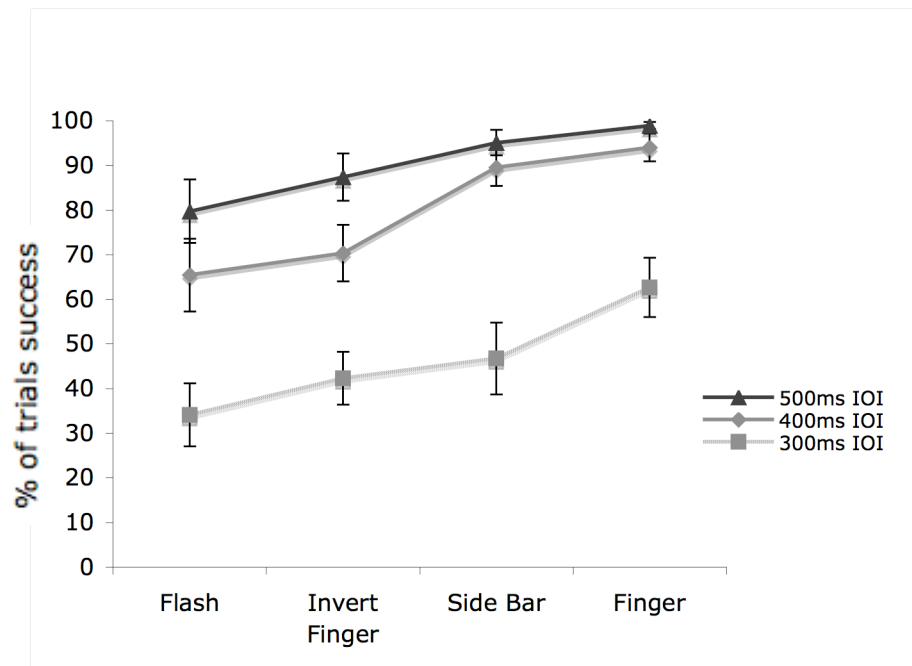


Figure 3.4: Percentage of successful trials in Experiment 2, as determined by a Rayleigh test of uniformity.

Analyses of tap timing showed that taps occurred earlier at the slower tempi. An ANOVA revealed a main effect of tempo on mean relative phase,  $F(2, 153) = 22.9, p < .001$ . On average, taps occurred 53 ms before the target in the slow 500 ms IOI condition, 5 ms after the target in the fast 400 ms IOI condition, and 49 ms after the target in the very fast 300 ms IOI condition (converted from mean relative phase). There was no effect of type of metronome on mean relative phase overall,  $F(3, 152) = .2, p > .8$ ; nor was there an effect of metronome at just the slowest, most-stable tempo,  $p > .8$ .

Experiment 2 demonstrated that the mere addition of spatial information on its own does not improve synchronization performance over flashing metronomes, as indicated by the equally poor synchronization for the incompatibly moving Inverted Finger and non-spatial Flash. Synchronization was greatly improved with spatial stimuli moving orthogonally to the to-be-produced movement; and compatible motion further facilitated synchronization performance. The anticipation tendency was greater at slower tempi.

### Experiment 3

In light of the facilitation observed in the first two experiments, Experiment 3 probed whether the maximum rate of visuomotor synchronization with compatibly moving targets could approach that of auditory-motor synchronization. Participants synchronized finger tapping with four types of metronomes: 1) auditory beeps; 2) an up-down moving bar compatible with finger movements; 3) a Flash; and 4) a Flash target interspersed with predictably intensifying “snowflakes,” dubbed *Fade*. The *Fade* metronome controlled for the possibility that the facilitation observed in moving metronomes stemmed from their continuous and predictable nature, rather than their

spatial translation (moving metronomes and the Fade metronome have a trackable cycle and, in a sense, provide more warning of their impending impulse point than does the Flash condition). Sequences were presented at even faster tempi: Target IOIs were 400 ms, 300 ms, and 240 ms.

### *Method*

#### *Participants.*

Ten Cornell students (3 women) aged 19-32 participated (including author MJH). Musical training ranged from 0-20 years ( $M = 6.5$ ) and produced no significant results. Participants received \$4.

#### *Materials.*

Stimulus sequences were presented with Matlab's PsychToolbox running on a 2.4 GHz MacBook Pro (NVIDIA GeForce 9600 video card) with its lid closed and driving an external CRT monitor at a refresh rate of 100 Hz (10 ms). PsychToolbox syncs visual presentation to the refresh rate allowing millisecond accurate timing for visual, as well as auditory stimuli. All sequences lasted 26 cycles. Visual metronomes at the 400 ms and 300 ms target IOIs consisted of 10 images per cycle, with each image lasting 40 ms and 30 ms, respectively; the 240 ms IOI sequences consisted of 6 images/cycle, with each image presented for 40 ms. Sequences are depicted in Figure 3.5.

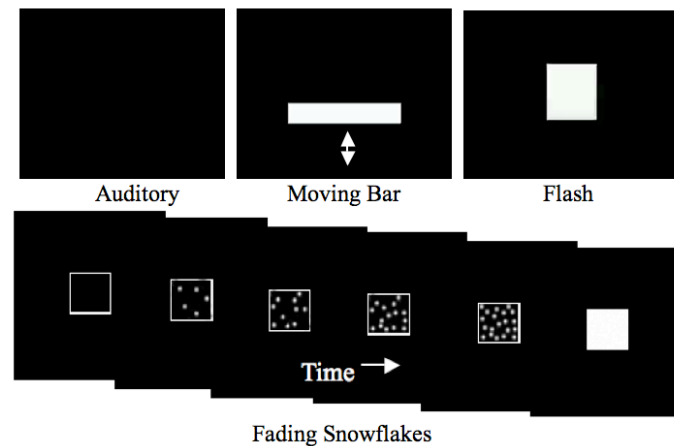


Figure 3.5: The four metronomes from Experiment 3.

Auditory sequences consisted of 40 ms long sine wave beeps at 440 Hz. The up-down moving bar was a 5 x 1 cm bar, with a 2.5 cm max displacement above the bottom of the screen for the 400 and 300 ms IOI trials and a 1.5 cm max displacement for the 240 ms IOI trials. The Flash was a 2 cm x 2 cm white square. The Fade metronome consisted of the Flash target interspersed with dots; it started with a blank screen, then added dots each successive image until the Flash onset, then subtracted dots until the blank (i.e. blank, 5 dots, 10 dots, 15 dots, 20 dots, FLASH, 20 dots, 15 dots,... etc. for 400 and 300 ms IOI trials, and blank, 10 dots, 20 dots, FLASH, 20 dots, 10 dots... for 240 ms IOI trials).

#### *Procedure.*

Participants sat in front of a computer monitor wearing Beyer Dynamic circumaural headphones and tapped on a light cardboard box fitted with a microphone. On a separate Mac G4 computer running Audacity at an 8000 Hz sample rate, taps were recorded on one channel, and trial onset markers from the stimulus computer were recorded on the other channel.

Each of the twelve trial types (3 tempi x 4 metronome types) was presented in random order in a block. The experiment consisted of 1 practice block and 10

experimental blocks (120 analyzed trials). The experiment lasted approximately 25 minutes.

### *Results and Discussion*

Tapping data were analyzed using circular statistical methods and the taps occurring during the first four targets of each trial were omitted from analyses. The percentage of successful trials by condition is shown in Figure 3.6. A 3 (tempo) x 4 (metronome type) ANOVA found a main effect of metronome type,  $F(3, 27) = 39.0$ ,  $p < .001$ ,  $\eta_p^2 = .81$ . Pair-wise comparisons showed that the synchronization performance with the Auditory metronomes was better than each visual metronome ( $ps < .01$ ). Among the visual metronomes, the moving bar yielded better synchronization performance than the Flash or the Fade ( $ps < .05$ ), and no difference was observed between the Flash and the Fade ( $p > .1$ ). Tempo also affected synchronization performance,  $F(2, 18) = 23.2$ ,  $p < .001$ ,  $\eta_p^2 = .72$ , with pairwise comparisons showing that performance was worse at faster tempi ( $ps < .05$ ). The tempo x metronome interaction,  $F(6, 54) = 3.5$ ,  $p < .01$ ,  $\eta_p^2 = .28$ , indicates that the fast tempos impede synchronization more for visual than auditory metronomes.

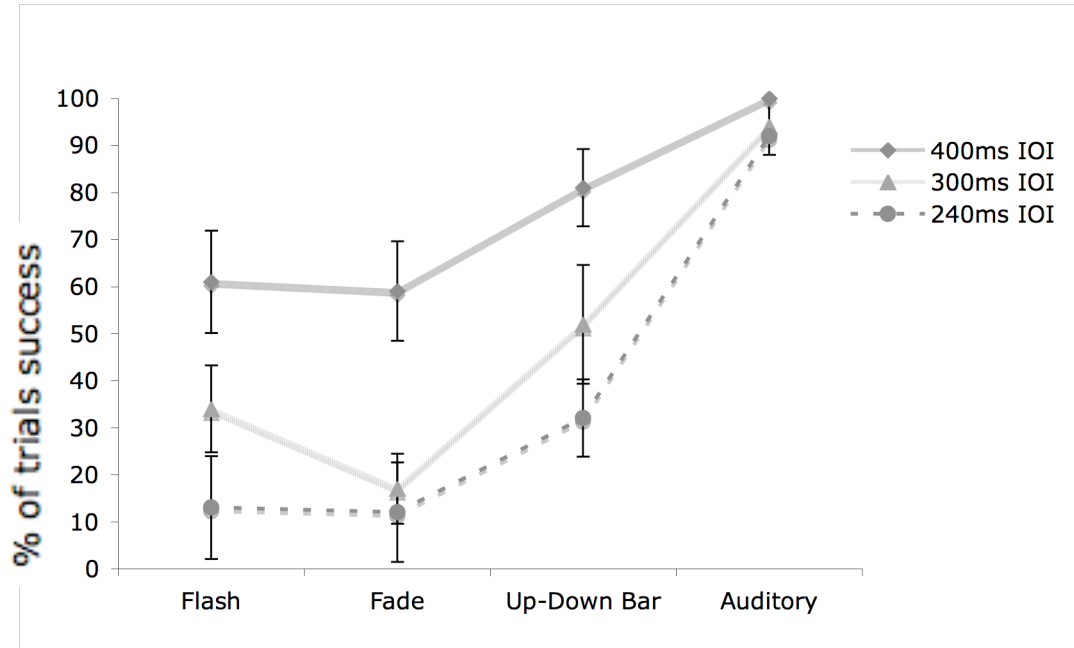


Figure 3.6: Percentage of successful trials in Experiment 3, as determined by a Rayleigh test of uniformity.

Taps tended to precede the targets, especially in the slowest tempo. A circular ANOVA revealed a main effect of tempo,  $F(2,117) = 4.34, p = .015$ . On average, taps occurred 42 ms before the target in the 400 ms IOI condition, 6 ms after the target in the 300 ms IOI condition, and 3 ms before the target in the 240 ms IOI condition (converted from mean relative phase). There was no effect of metronome type on mean relative phase overall,  $F(3,116) = 2.39, p = .072$ ; nor was there an effect of metronome at just the slowest, most-stable tempo,  $p > .8$ .

Experiment 3 demonstrates that synchronization performance is more stable in the auditory domain, even compared to compatibly moving visual stimuli. The Fade metronome did not improve synchronization over the Flash, thus we can confidently conclude that the facilitation with the moving bar is due to its compatible *spatial* component, rather than its predictability.

## General Discussion

These results demonstrate that compatible spatial information greatly facilitates visuomotor synchronization. In Experiment 1, participants' synchronization performance was dramatically better with the three moving metronomes (similar in amplitude, size, and trajectory) than the flashing metronome. No unique advantage was observed for synchronization with biological forms in particular, despite the representational overlap for seeing bodily forms and for producing movements in the extrastriate body area. Our stimuli did not contain biological motion, but future work should explore synchronization with metronomes containing biological trajectories of acceleration/deceleration. Experiment 2 demonstrated the importance of directional compatibility between the metronome and body movement. Synchronization performance was equally poor for the action-incompatible Inverted Finger and the Flash. The directional mismatch between target stimulus (upward) and tap response (downward) presumably caused interference, thereby negating the spatial facilitation. Performance improved when tapping with an orthogonal (i.e. non-interfering and non-compatible) sideways moving bar, and best performance occurred with the highly compatible (in direction, amplitude, and size) Finger video.

In Experiment 3 (and much additional pilot work employing stimuli that continuously faded into color bursts), no advantage was observed for a predictable Fade metronome. Thus, rather than predictability, the spatial component appears to be the crucial facilitative factor, probably due to the visual system's proficiency at processing spatial information.

Rough estimates of a "synchronization threshold" (50% success rates, Repp, 2003) for compatibly moving metronomes in Experiments 2 and 3 converge around 300 ms IOI for the untrained, novice-tapper participants. Two participants in Experiment 3 easily synchronized at the fastest tempo: 240 ms IOIs; and future work



could examine effects of training on this uncommon task or examine performance of “hand-eye experts” such as athletes or video-gamers. Although this rough threshold is much faster than previously established, the advantage for synchronization in the auditory modality remains, as participants could successfully synchronize with the auditory stimuli, even at the 240 ms IOI tempo.

The compatibility effects support the notion that temporal information for action is not coded in an independent, action-neutral domain (i.e., in a specialized, isolated timing center that extracts temporal information from perceptual systems regardless of orientation, then sends this on to an isolated action planning system). Rather, temporal information here appears to be computed in a task-dependent, action-oriented manner (Ivry & Spencer, 2004). Additionally, the compatibility effects between perceived and produced events can be explained in terms of the common-coding theory of perception and action (Hommel, Müsseler, Aschersleben, & Prinz, 2001). In this theory, sensory and motor codes share a common representational medium; sensory information of a downward moving target converges on a shared abstract feature code, which spreads activation to the motor system, pre-specifying or biasing it toward downward action. Conversely, an upward moving sensory target will bias action toward upward movement and interfere with the downward goal.

Theoretical accounts of motor control that employ forward models suggest that motor commands to the muscles are accompanied by an efference copy that predicts sensory consequences of movement (Blakemore, Wolpert & Frith, 2002; Wolpert & Kawato, 1998). Discrepancies between this prediction and the actual sensory feedback (both direct somatosensory and visual or auditory information indirectly resulting from action) allow rapid adjustment to the movement. In our experiment, the incompatible Inverted Finger stimuli yielded a constant lack of correspondence between visual information and efference copy prediction and somatosensory

feedback, which would lead to increased adjustment and hence higher variability and difficulty. Conversely, a tight correspondence between these signals not only evinces good performance, but also gives us a sense of agency (Farrer & Frith, 2002). When tapping with the compatible Finger video, many participants responded in post-test questioning, that they felt that the video was *their* hand or that they were controlling the video. Such a misattribution of ownership and/or agency might stem from the close correspondence between visual, somatosensory, and motor prediction signals, (see also Knoblich & Sebanz, 2005).

To sum, our results demonstrate that visuomotor synchronization performance is greatly facilitated by compatible motion, possibly due to the visual system's proficiency at processing spatial information and the tight linkages between perceptual and action systems; however an auditory advantage in sensorimotor synchronization persists.

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## CHAPTER 4

### IT'S ALL IN THE TIMING: INTERPERSONAL SYNCHRONY INCREASES AFFILIATION<sup>16</sup>

#### Abstract

The tendency to mimic and synchronize with others is well established. Although mimicry has been shown to lead to affiliation between co-actors, the effect of interpersonal synchrony on affiliation remains an open question. The authors investigated the relationship by having participants match finger movements with a visual moving metronome. In Experiment 1, affiliation ratings were examined based on the extent to which participants tapped in synchrony with the experimenter. In Experiment 2, synchrony was manipulated. Affiliation ratings were compared for an experimenter who either a) tapped to a metronome that was synchronous to the participant's metronome, b) tapped to a metronome that was asynchronous, or c) did not tap. As hypothesized, in both studies, the degree of synchrony predicted subsequent affiliation ratings. Experiment 3 found that the affiliative effects were unique to *interpersonal* synchrony.

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<sup>16</sup> Hove, M. J. & Risen, J. L. (in press). It's all in the timing: Interpersonal synchrony increases affiliation. *Social Cognition*. Copyright © by Guilford Publications, Inc. Adapted with permission.

## Introduction

Interpersonal coordination is typically divided between behavioral matching (e.g., mimicry) and interactional synchrony (e.g., movement matched in time) (Bernieri & Rosenthal, 1991). A good deal of research has been conducted to understand the mechanisms, moderators, and effects of mimicry. Less attention has been devoted to synchrony. Although widespread anecdotal evidence suggests that moving synchronously with others is associated with affiliation (e.g., Macdonald & Wilson, 2005) and it has been argued that interpersonal coordination may have been selected evolutionarily for its role in social cohesion (Freeman, 2000; McNeill, 1995), the causal effect of interpersonal synchrony on affiliation has not been experimentally established. The current research addresses this issue.

### *Behavioral Matching*

Behavioral matching, the well-documented tendency to mimic an interaction partner in body posture, laugh, speech accent, and syntax (for a review see Lakin, Jefferis, Cheng, & Chartrand, 2003), has been demonstrated to develop early and occur automatically. In addition, research suggests that mimicry promotes affiliation. For example, when a confederate mimicked participants' posture and movements, they liked the confederate more (Chartrand & Bargh, 1999). Behavior matching does not require that the behaviors be matched in time. In fact, research on mimicry often includes a lag, such that mimicry is adopted several seconds after the original behavior. If the delay is too short, the participant is more likely to detect the mimicry (Bailenson, et al., 2004), and overt detection can have negative effects on affiliation (Bailenson, Yee, Patel, & Beall, 2007).

Mimicry is thought to occur because of the tight neural link between perception and action (e.g., Iacoboni, et al., 1999). According to common coding theory, perception and action plans are coded in a common representational medium



(Hommel, Musseler, Aschersleben, & Prinz, 2001), and research on mirror neuron systems supports this claim (e.g., Gallese, Keysers, & Rizzolatti, 2004). Perceiving another's movements activates one's own action system for that same movement (Knoblich & Sebanz, 2006; Rizzolatti, Fadiga, Gallese, & Fogassi, 1996), increasing the likelihood and ease of initiating a matched action (Brass, Bekkering, & Prinz, 2001).

These perception-action linkages have also been proposed to play a role in generating affiliation and social cohesion (Chartrand & Bargh, 1999; Dijksterhuis & Bargh, 2001, Gallese, 2003; Hurley, 2008). Perceiving an agent's action automatically and directly maps onto the observer's action system, creating a neural coupling between the agent and observer (Blakemore & Decety, 2001; Semin & Cacioppo, 2008). Thus, shared representations for perception and action naturally extend to shared representations for self and other (Gallese, 2003; Hurley, 2008). This "self-other equivalence" may promote meaningful social bonds and interpersonal closeness by helping people understand others' actions (e.g., Iacoboni, 2005; Meltzoff, 2005) or by increasing people's tendency to project positive views of the self to others (Otten & Wentura, 2001; Smith, 2008). Note that self-other "overlap" in perception/action systems resonates with earlier metaphorical treatments of self/other overlap in social interactions. For example, building on work by James, Mead, and Lewin, Aron and colleagues (1991) established that close interpersonal relationships are characterized by "including the other in the self." And, more recently, Fiske (2004) proposed that one major type of social relationship is a communal sharing relationship, wherein the self and other are deeply connected.

### *Synchrony*

Synchronized behaviors are those that are matched in time. Synchrony can occur with different actions, such as the coordinated movements of an athletic team or

an orchestra; or with the same actions, such as pairs walking in stride (cf. van Uelzen et al., 2008). Unlike behavioral matching, synchrony requires anticipating others' behaviors to coordinate movement timing (Keller, 2008; Sebanz, Bekkering, & Knoblich, 2006). In conversation, for example, the listener's body moves in synchrony with the speaker's rhythm of speech (Condon & Ogston, 1966; Hadar, Steiner, & Rose, 1985); and even neonates have been shown to synchronize movements with speech rhythms (Condon & Sander, 1974). The unintentional tendency for two or more people to entrain their periodic movements is often examined with dynamical systems approaches. For example, when seated next to each other, two individuals' swinging legs naturally come into phase (Schmidt, Carello, & Turvey, 1990), as do their rocking chair periodicities (Richardson et al., 2007), and finger oscillations when instructed to attend to the others' movements (Oullier et al., 2008). Larger groups also synchronize their movements as exemplified by phase-locked rhythmic applause in concert halls (Neda et al., 2000). Despite the rich literature documenting synchrony, however, there is relatively little research examining the underlying mechanisms of interpersonal synchrony or the effects of being in sync.

Because synchrony relies on fine-grained timing, structures such as the cerebellum and basal ganglia are likely involved (Ivry & Spencer, 2004). And, recent work suggests that the tight perception-action linkages that promote mimicry may also be involved in synchrony. A recent EEG experiment on interpersonal finger tapping revealed an oscillatory component that seems to enhance mirror system activity during synchronous, but not asynchronous behavior (Tognoli, Lagarde, DeGuzman, & Kelso, 2007).

Thus, as with mimicry, synchrony may promote self-other overlap in neural representation, with corresponding effects on affiliation. In addition, because synchronous behavior is often associated with close, communal relationships (Smith,

2008), synchronous behavior may be interpreted as evidence of a close relationship, which in turn, could promote more closeness. Whether stemming from direct neural overlap for self and other, and/or more indirect interpreted cues for a shared relationship, we contend that *synchronous* behaviors will promote more affiliation than matched behaviors alone (e.g., Chartrand & Bargh, 1999; LaFrance, 1982). That is, holding behavior constant, we predict that synchrony will boost affiliation.

Past research offers supportive, but inconclusive evidence for this claim. Happily married couples, for example, showed more responsive body language than dissatisfied couples during counseling sessions (Julien, Brault, Chartrand, & Begin, 2000). Additionally, in mock student-teacher interactions, the interactants' ratings of rapport correlated with outside observers' ratings of movement synchrony (Bernieri, 1988); however, critics contend that observers' ratings might reflect the positivity, not the synchrony of interaction (Capella, 1990). Moreover, based on these correlational results, it is possible that liking leads to more synchrony (rather than synchrony leading to liking). The current experiments examined affiliation following an interaction in which the degree of synchrony was quantified (Experiments 1-3) and manipulated (Experiments 2 and 3).

## Experiment 1

Experiment 1 tested the relationship between affiliation and objectively quantified (rather than subjectively rated) synchrony. We predicted that participants who tapped in synchrony with the experimenter would like the experimenter more.

### *Method*

#### *Participants.*

Forty-four Cornell University students (19 females) voluntarily participated.

### *Materials and Procedure.*

Participants tapped their right index finger on a Roland SPD-6 drum machine, keeping time with a moving target on a computer screen. The 1 cm wide target bar oscillated 2 cm vertically within a box icon. Participants tapped when the bar hit the bottom of the box, making finger and target movements compatible in amplitude and direction. The experimenter sat to the participant's right, matching her finger movements to a separate moving target.<sup>17</sup> A divider placed on the screen obstructed the view of the other's target so that participants and the experimenter could not see each other's target. The experimenter tapped on the drum machine's right-most pad, while the participant tapped on its left-most pad (approximately 25 cm apart). Each other's finger movements were peripherally visible and taps produced a light, audible 'thud.'

The tapping portion of the experiment consisted of 12 trials and lasted approximately 2.5 minutes. Half of the trials were presented at a fast tempo and half at a slow tempo to ensure that participants tracked their targets, rather than simply

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<sup>17</sup> The experimenter explained that she would tap to her own target and did not offer an explanation for her actions (no participant asked why or seemed troubled by it).

memorizing the tempo. Participant's targets occurred 24 times per trial with inter-onset-intervals (IOI) of 510 ms in fast trials and 570 ms in slow trials.<sup>18</sup>

After the tapping task, participants filled out a questionnaire about the task (difficulty, enjoyment, perceived tapping success, etc.), and about the participants' state (overall mood, mental exhaustion, and physical exhaustion). The critical measure was participants' affiliation with the experimenter. All responses were on a 9-point Likert scale. The measure of affiliation: "How likable was the experimenter?" was anchored at 1 with "extremely dislikable" and at 9 with "extremely likable." A final form probed for suspicion. Participants placed questionnaires in a large "anonymous" envelope.

The critical measure for tapping was the degree of interpersonal synchrony between the participant and experimenter. The degree of synchrony was analyzed in terms of 1) the mean unsigned asynchrony between the participant's and experimenter's taps and 2) the percentage of participant and experimenter's taps that

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<sup>18</sup> The experimenter tapped with a separate metronome randomly assigned to be either coincident or 50% faster than the participant's. During this short task, however, participants did not acquire the skill necessary to tap consistently with their target (see Results and Discussion). Because participants did not keep accurate time with their own metronome, we could not compare those that were matched with those who were mismatched with the experimenter. Instead, our analyses collapsed across the intended manipulation and examined actual tapping behavior. Experiments 2 and 3 used a longer task (and practice trials) to ensure that participants tapped with their metronome, allowing us to make comparisons across randomly assigned conditions.

occurred “together,” where together was defined as co-occurrence within a 100 ms temporal integration window. Previous research indicates that when two auditory events occur within 100 ms, they are integrated in a bound unit (Yabe et al., 1998).

### *Results and Discussion*

In this short task, participants did not acquire the skill to tap consistently with their target metronome. On average, participants’ consistency between taps and targets (i.e., circular variance (CV) = .49; Fisher, 1993) was above the previously used threshold for visuomotor synchronization success (CV = 0.42; Repp, 2003). We examined interpersonal synchrony, however, by examining the actual tapping of participants and the experimenter.

As predicted, the degree of *interpersonal* synchrony between participants and the experimenter predicted how much participants liked the experimenter. Participants who tapped closer and more consistently with the experimenter rated her more likeable on the subsequent questionnaire. High likability ratings corresponded with small mean asynchronies between the participant and experimenter ( $r = -.372, p = .014$ ) and with high percentages of taps occurring within 100 ms ( $r = .386, p = .012$ ). Likability ratings did not correlate with other questionnaire measures (task enjoyment, task difficulty, and perceived tapping success for themselves and the experimenter), nor with individual tapping performance (tempo or variability of tapping,  $ps > .3$ ).

These results demonstrate a positive relationship between synchrony and affiliation even when synchrony was objectively quantified. However, the correlational analysis makes the causal direction unclear. Did participants like the experimenter because they tapped in synchrony with her or did they tap in synchrony because they liked her? Experiment 2 was designed to test the causal direction of the relationship.

## Experiment 2

To determine whether being “in sync” creates a feeling of affiliation, Experiment 2 manipulated the experience of synchrony and included a base-line measure of likeability. To successfully manipulate the experience of synchrony, participants engaged in a long tapping task so that they would achieve the skill necessary to keep accurate time with their target.

### *Method*

#### *Participants.*

Seventy-four Cornell University students (54 females) participated for course credit. They were randomly assigned to one of three between-subjects conditions: tapping in synchrony with the experimenter ( $n = 26$ ), tapping out of synchrony with the experimenter ( $n = 24$ ), or tapping alone ( $n = 24$ ). Five were excluded from analysis due to suspicions about the hypothesis (3 from the synchronous condition, and 2 from the asynchronous condition).

#### *Materials and Procedure.*

As in Experiment 1, participants tapped their right index finger keeping time with a moving target, while seated next to the experimenter. The tapping portion of the experiment consisted of 4 practice trials and 32 test trials. Half of the trials were presented at a fast tempo and half at a slow tempo. In all three conditions, the participant's targets occurred 24 times per trial with IOIs of 520 ms in fast trials and 600 ms in slow trials. In the synchrony condition, the experimenter tapped with a separate moving target matched in tempo to the participant's rates of 520 and 600 ms IOIs. In the asynchrony condition, the experimenter tapped with targets that were 33% faster than the participant's, or 390 and 450 ms IOIs. In the alone condition, the

experimenter rested her hands in her lap. The tapping task lasted approximately 10 minutes.

Prior to tapping, a preliminary questionnaire checked for baseline differences in affiliation with the experimenter. Participants were told that “numerous experimenters were running the study and in order to check for differences,” they should rate the clarity of the instructions and the experimenter’s friendliness (a proxy for likability). In actuality, one experimenter, who was blind to the hypothesis, ran all participants. After the tapping task, participants filled out a questionnaire about the task (difficulty, enjoyment, perceived tapping success, etc.), and about the participants’ state (overall mood, mental exhaustion, and physical exhaustion). As in Experiment 1, the critical measure was participants’ affiliation with the experimenter. A final form probed for suspicion. Again, the critical measure for tapping was the degree of interpersonal synchrony between the participant and experimenter.

## *Results and Discussion*

### *Affiliation and Measured Synchrony*

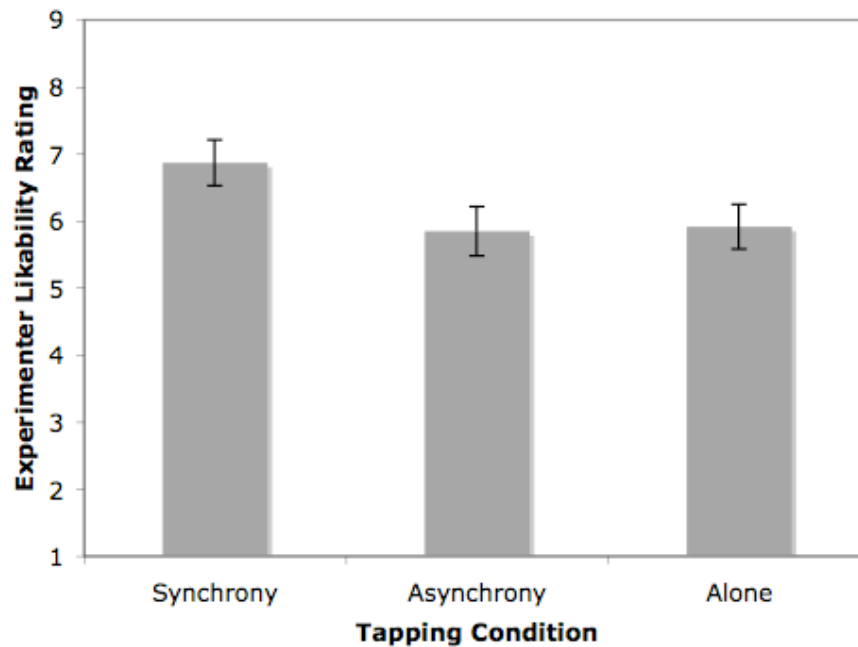
Replicating Experiment 1, the degree of *interpersonal* synchrony between the participant and experimenter predicted how much participants liked the experimenter. Participants who tapped closer in time and more consistently with the experimenter liked her more. Across conditions, high likability ratings correlated with small mean asynchronies between the participant and experimenter ( $r = -.418, p = .005$ ), and with high percentages of taps occurring within the 100 ms integration window ( $r = .401, p = .007$ ). When we control for base-line ratings, the partial correlations remain significant ( $ps = .001$ ). There was no relationship between participant’s individual tapping performance (tempo or variability of tapping) and likability ratings ( $ps > .3$ ).

### *Affiliation and Manipulated Synchrony*



Measures of individual tapping indicated that participants successfully matched their target metronome in this long task. Participants' consistency between taps and targets ( $CV = .36$ ) was below the threshold for visuomotor synchronization success and did not differ between conditions ( $p > .6$ ). Participants' tapping tempo (Mean ITI) was accurate in all conditions for fast ( $M = 520.7$ ) and slow trials ( $M = 595.6$ ); and did not differ between conditions ( $ps > .9$ ). Results for experimenter tapping tempo indicate that she also successfully tapped at the target frequency in all conditions. Thus the manipulation was successful; participant and experimenter taps were more coordinated in the synchrony condition than the asynchrony condition (in terms of mean asynchronies and percent of taps co-occurring within 100 ms,  $ps < .001$ ).

The critical test showed that participants in the synchrony condition liked the experimenter significantly more ( $M = 6.87$ ) than those in the asynchrony condition liked her ( $M = 5.91$ ),  $t(43) = 2.48$ ,  $p = .017$ ,  $d = 0.74$  (see Figure 4.1). There were no differences between groups in the preliminary questionnaire on friendliness,  $p > .4$ , and the results remain significant when controlling for base-line ratings of friendliness.



*Figure 4.1.* Mean likability ratings by tapping condition in Experiment 2. Error bars represent standard error.

Likability was not mediated by any of the other measured subjective factors. In fact, there were no significant differences between synchrony and asynchrony conditions observed in t-tests on task enjoyment, task difficulty, mood, physical exhaustion, mental exhaustion, or perceived success of their own or the experimenter's synchronization with their respective metronome ( $.1 < ps \leq .9$ ).

The alone condition was included to test whether being “in sync” enhanced feelings of affiliation. We predicted that, compared to the alone condition, experiencing synchrony with the experimenter would increase feelings of affiliation for her. Thus, we predicted that those in the synchronous condition would like the experimenter more than those in the control condition and asynchronous condition liked her. Alternatively, being “out of sync” might diminish feelings of affiliation, resulting in lower experimenter likability ratings by participants in the asynchrony

condition than the alone and synchrony conditions. For example, if participants actively inhibited the tendency to fall into sync, they may have inferred that it was not a close relationship. Finally, it was possible that those in the synchronous AND asynchronous conditions would like the experimenter more than those in the control condition because both of the experimenter tapping conditions included behavioral matching, while the control condition did not. This third possibility seemed unlikely because participants were completely aware of the behavioral matching (regardless of whether they were aware of the synchrony). In other words, because the effect of mimicry on affiliation seems to depend on it going unnoticed, we did not expect that the behavior matching in the asynchronous condition would promote affiliation compared to the non-tapping control group.

Following a one-way ANOVA ( $F(2,66) = 2.69, p = .075$ ), we used the least significant difference test to make planned comparisons with the alone condition. We observed higher ratings of experimenter likability in the synchrony condition ( $M = 6.87$ ) than the alone condition ( $M = 5.92$ ),  $p < .05$ , and no difference between the alone and asynchronous conditions,  $p > .9$  (see Figure). These results indicate that affiliation increases after experiencing interpersonal coordination, rather than decreasing after a lack of coordination. In addition, the results reaffirm the importance of behavioral matching going undetected if it is to increase affiliation. This study is the first of which we are aware to demonstrate a causal influence of synchrony on affiliation.

### Experiment 3

Experiment 3 tested our claim that synchrony promotes feelings of affiliation because of the interpersonal nature of the coordination. It is possible that participants in the first 2 studies liked the experimenter more simply because they were

experiencing synchrony (and not necessarily interpersonal synchrony).<sup>19</sup> Experiment 3 tested whether affiliation would arise from experiencing synchrony that was inanimate, rather than interpersonal.

### *Methods*

#### *Participants.*

Forty-seven Cornell University students participated for course credit.

#### *Materials and Procedure.*

Participants sat next to a non-tapping experimenter and tapped along with a visual moving target (36 total trials at 520 and 600 ms IOIs), while an auditory metronome (matched in loudness to the tapping) pulsed either synchronously or asynchronously with the participant's visual target, or was silent in a third between-subjects condition. Afterwards, participants completed the same set of questionnaires as they did in the previous studies. Thus, participants' experience was identical to Experiment 2, except that they tapped either in sync or out of sync with a metronome rather than with the experimenter.

### *Results and Discussion*

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<sup>19</sup> Perhaps tapping in sync increased processing fluency, which, in turn, increased participants' general hedonic state and led them to like the experimenter more. This alternative seems unlikely because synchrony was not related to their feelings about the task (i.e., how much they liked the task or how difficult they found it) or their mood.

As in Experiment 2, measures of individual tapping indicated that participants successfully matched their target metronome ( $CV = .26$ ). Thus, the manipulation of synchrony was successful.

We found no differences between conditions for experimenter likability ratings ( $p > .17$ ). Tapping in synchrony with a metronome did not lead participants to like the experimenter sitting beside them more ( $M = 6.88$ ) than when the metronome was out of sync with their tapping ( $M = 7.60$ ) or was silent ( $M = 6.50$ ). In addition, as in the previous experiments, there was no effect of condition on task enjoyment, difficulty, or mood. Thus it appears that the degree of *interpersonal* synchrony was the critical factor contributing to likability in Experiments 1 and 2 rather than a general preference for any experience of synchrony (note, however, that this conclusion is drawn from a null result and therefore should be interpreted cautiously).

### General Discussion

The current experiments demonstrate that interpersonal synchrony leads to affiliation. First, the measured degree of interpersonal synchrony in Experiments 1 (3 minute tapping task) and 2 (10 minute tapping task) correlated with subsequent affiliation ratings. In addition, the causal direction was examined in Experiment 2, and we found that participants assigned to tap in synchrony with the experimenter liked her more than participants assigned to tap out of synchrony or alone. Because the participant's and experimenter's movements were matched, we can be certain that the effect was due to the timing of the movements (i.e., affiliation was produced by synchrony rather than mimicry). Together with Experiment 3, we conclude that *interpersonal* synchrony was the critical factor contributing to likability rather than a general effect of synchrony.

The matched actions during the asynchrony condition in Experiment 2 fall within the typical definition of mimicry,<sup>20</sup> but failed to boost affiliation ratings compared to the alone control condition. This finding reaffirms the need for mimicry to go unnoticed in order for it to increase affiliation (Bailenson, Yee, Patel, & Beall, 2007). What about synchrony? Must it go unnoticed as well? In our studies, participants were asked in the suspicion probe whether they noticed anything about how their tapping related to the experimenter's tapping. A handful of participants reported the relationship incorrectly (e.g., claiming that they were not tapping together when they were assigned to tap together or vice versa), a minority of participants correctly reported the tapping relationship, and the majority of participants did not report any specific relationship. There was no difference in affiliation ratings for those who correctly reported whether they were in sync and those who did not notice the relationship (there were not enough incorrect participants to compare them to the others). Although most participants did not report the tapping relationship, because the synchrony was rather overt, we would not claim that it went entirely unnoticed. Future work should examine whether noticing synchrony interferes with, promotes, or does not affect affiliation.

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<sup>20</sup> A traditional account of mimicry simply requires that actions match in form.

Recently, however, Semin and Cacioppo (2008) suggested that mimicry only describes non-periodic matched movements. Thus, according to Semin and Cacioppo, there was no mimicry in the synchronous and asynchronous conditions because the actions were periodic. Regardless of one's perspective on mimicry, however, the difference between the two conditions is the presence or absence of synchrony.

While we show that synchrony can have affiliative effects similar to previous work on mimicry, open questions remain for whether moderators of mimicry also apply for synchrony. For example, do people synchronize less with a disliked or stigmatized individual or synchronize more when their self-construal is interdependent rather than independent and when they have an affiliation goal?

In addition, it is unclear whether synchrony and mimicry rely on the same neural mechanisms and whether affiliation results for the same reason in each case. Mimicry research suggests that affiliation occurs because of self-other representational overlap. The affiliative effects of synchrony may rely on this same neural mechanism. During interpersonal synchrony, when self- and other- produced movements are highly aligned in both form and time, the neural activations for perceptions of self and other closely overlap, which may interfere with the ability to discriminate self- versus other- produced action (Georgioff & Jeannerod, 1999), in essence blurring the self/other distinction. Less self/other distinction potentially offers a closeness and ease of understanding that yields affiliation. Or during self-other overlap, positive views of ourselves may extend to the other (e.g., Galinsky, Martorana, & Ku, 2003). Or, within a dynamical systems framework, people could experience greater social synergy when coupled oscillators are in synchrony because energy in the dyadic system is minimized in this more stable coordination pattern (Marsh, Richardson, Baron, & Schmidt, 2006).

Alternatively, because synchronous behaviors are associated with communal relationships, it is possible that people infer closeness when they notice synchrony. For example, touch, physical proximity, shared resources, and synchronized movements act as cues to a communal sharing relationship (Fiske, 2004; Smith, 2008). Future work could look at more covert, subtle forms of synchrony in order to decouple higher-level cues for a shared relationship from lower-level self/other overlap. In addition, future

work could manipulate synchrony by using a confederate to reduce the possibility that the effects require a “higher status” individual.

While the exact mechanism remains clouded, the clear effect of interpersonal synchrony on affiliation extends similar well-documented effects in mimicry by incorporating the crucial aspect of time. Freeman (2000) argues that music and dance evolved to serve as a technology of social bonding. Bandmates often report a great deal of connection. And it’s no wonder that couples’ synchronous movements in dancing (not to mention in sex) are an affiliative bonding activity – while you may not know if you are in your partner’s heart, you know you are in their mind. In a world rife with isolation, the aligned representations in interpersonal synchrony may provide a means for togetherness and connection.



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## APPENDIX

### METHODOLOGICAL NOTE ON CIRCULAR STATISTICS

Synchronized tapping experiments are typically analyzed using linear time series methods, wherein taps and targets are aligned on a linear time scale and their respective asynchronies are calculated. However, linear methods are not ideal for a few reasons. First, a single outlier tap can skew both mean asynchrony and variability measures. For example, in a synchronized tapping experiment, participants commonly stop tapping prematurely and then start up again, resulting in few errant taps. If the majority of taps for such a trial occur 20 to 40 ms before the target, but 2 taps occur around 240 ms before the target, the resulting mean asynchrony does not reflect performance timing. To avoid such pitfalls, one must often scan data sets for aberrant trials and outlying taps, which can be labor intensive. Additionally, with linear transformations of periodic data, one must decide how to represent the range. For example, if the target IOI is 500 ms, asynchronies could range from 0-500 ms (e.g., 480 ms is slightly before the target, and 20 ms is slightly after the target); or from -250 to +250 ms (where negative values occur “before the target” and positive values occur “after the target”); either way, the ends of the range are identical values. This discontinuity at the end of the linear range can distort analyses and is known as the notorious cross-over problem; for example the mean of asynchrony values 480 and 20 is 250, which does not sensibly reflect the mean timing.

These issues can be circumvented to some extent with circular statistical methods (e.g., Fisher, 1993). Circular statistics can be used with periodic data sets, such as angles, days of the week, or tap times. Each tap in a trial is mapped onto a unit circle in terms of its relative phase (0-360°) from the periodic metronome target (always at

0°). The relative phase of taps slightly after the target is 0-90° and slightly before the target is 270-360°.

Circular methods assist in accurately assessing the mean asynchrony (mean direction) of taps. Again the *numerical* mean of 355° and 5° is 180° and is non-representative. However the *angular* mean (or mean direction) yields a more representative mean. The mean direction of a series of angles is calculated by taking each angle's sine and cosine individually, then calculating the arctan of ( $\sum \text{sins} / \sum \text{cosines}$ ). Using this technique the angular mean of 355° and 5° is 0°, which yields an accurate depiction of the average of these circular data points.

The variability of taps can also be assessed with circular methods. Circular variance is a measure of dispersion around the unit circle, and in order to calculate circular variance, one must first calculate the mean resultant length (Rbar) of the vector resultant of all data points. The mean resultant length (Rbar) ranges from 0 to 1: where Rbar = 1 when all points are coincident on the unit circle; and Rbar = 0 implies a uniform distribution of points around the unit circle if you assume a unimodal von Mises distribution (the circular equivalent of a Gaussian distribution), however Rbar = 0 can also indicate a highly structured bi-modal distribution. Circular variance  $V = 1 - \text{Rbar}$ ; where  $0 \leq V \leq 1$  and lower V indicates a more concentrated distribution around the unit circle (Fisher, 1993).

An indicative measure of synchronization performance is the percentage of trials in which tap-to-target phases never stabilize. Linear treatments typically define a trial as successful if the variability of tap-to-target phases is below a certain threshold. Circular treatments have developed a method to test a sample of unit vectors for uniformity of direction. The Rayleigh test of uniformity tests the null hypothesis of a non-uniform distribution of tap-to-target relative phases against the alternative hypothesis of a unimodal distribution of tap-to-target relative phases. This test is



based on the mean resultant length, and the null hypothesis of uniformity is rejected if  $R_{\text{bar}}$  is larger than some critical value. Thus each trial's synchronization performance is subjected to a Rayleigh test and the null hypothesis of non-uniformity is rejected if the Rayleigh test p-value was less than .05; these trials had a uniform distribution of tap-to-target relative phases and were defined as successful, as opposed to trials with a non-uniform distribution of taps that would occur with irregular tapping or phase drift. We can then compare the percentage of successful trials by condition.

While circular treatments hold some advantages over linear treatments, they also have their drawbacks. First and foremost, comparing circular data in multifactor designs is problematic as “very little statistical methodology is available for analyzing data from experiments in which a circular response has been measured at various levels of two or more explanatory variables” (Fisher, 1993, p. 133). Multifactor ANOVAs for circular data do not exist, making it impossible to have factors benefit from dependencies and the relative apportioning of unique and shared variance. This “dearth of applicable methodology is especially frustrating when contrasted with the versatile framework provided by (generalized) linear models in the analysis of a scalar response” (Presnell, Morrison, & Littell, 1998, p. 1068). Some techniques have been proposed (such as the *spherically projected multivariate linear* (SPML) model by Presnell and colleagues, 1998), but have not exactly caught on. This leaves a few options for analyzing mean circular directions: 1) Run separate one-way circular ANOVAs for tempo and for type of metronome, which suffers from ignoring dependencies based on participant or the unaccounted factor. This in essence creates a highly conservative test. 2) Calculate mean directions using circular methods, then translate into linear coordinates and run a multifactor ANOVA. With this option, adding weights into the analysis based on circular variance can minimize the skew that would result from linearly analyzing outlier data points.

Finally, linear treatments are generally accurate (especially with data sets containing low variability) and when I have run both linear and circular analyses, they typically converge nicely. There is a slight learning curve with circular techniques, and it was a fairly labor intensive to write matlab scripts to perform the circular tests. But others have developed toolboxes for both R and matlab (e.g., Berens & Velasco, 2009), which are easily available for download. Overall, circular methods are a nice way to deal with periodic data, such as in rhythmic synchronization experiments.

## REFERENCES

- Fisher, N. I. (1993). *Statistical analysis of circular data*. Cambridge: Cambridge University Press.
- Presnell, B., Morrison, S. P., & Littell, R. C. (1998). Projected multivariate linear models for directional data. *Journal of the American Statistical Association*, 93, 1068-1077.